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Internal Temperature Variation on Spontaneous Combustion of Coal Gangue Dumps under the Action of a Heat Pipe: Case Study on Yinying Coal Mine in China

Na Zhao [1], Yongbo Zhang [1,*], Xuehua Zhao [1], Jinrong Niu [2], Hong Shi [3], Na Yang [1], Tong Gao [1] and Lina Guo [4]

1 College of Water Science and Engineering, Taiyuan University of Technology, Taiyuan 030024, China
2 Yangquan Yinying Coal Mine, Yangquan 040500, China
3 College of Environmental Science and Engineering, Taiyuan University of Technology, Taiyuan 030024, China
4 College of Ecology, Taiyuan University of Technology, Taiyuan 030024, China
* Correspondence: zhangyongbo2021@sina.com; Tel.: +86-138-3460-6106

Abstract: Coal gangue spontaneous combustion is a serious catastrophe associated with mining activities. Generally, the areas of coal gangue spontaneous combustion are regions of tremendous heat accumulation. Mastering the regularity of deep temperature distribution and eliminating internal heat is an effective method to control spontaneous combustion. In this study, using self-developed heat pipe (HP) and intelligent cloud monitoring software, three sets of single pipe experiments were conducted in different temperature areas of the coal gangue dump in Yinying Coal Mine. A fitted model between shallow and deep temperatures was established using the least squares method to perform goodness-of-fit tests and significance analysis, and to analyze the internal temperature variation under the action of an HP. The results show that the quadratic model fits better and the regression is significant, and can be used as an empirical regression formula for the shallow temperature estimation of the deep temperature. The temperature was clearly suppressed by the HP, and the average cooling range reaches 21.44% within 700 h. However, the temperature of the control group without an HP continued to rise by 8%. In the three experimental groups, the effective control radius of the single HP was 3 m. The best cooling was achieved when the gangue depth was 1 to 4 m and the temperature was between 90 °C and 450 °C. The study shows that the HP has a great effect on thermal removal and inhibits spontaneous combustion of the gangue. In addition, this paper also provides a theoretical basis for the technology of HP treatment of spontaneous combustion gangue dumps.

Keywords: spontaneous combustion; coal gangue dump; heat pipe; fitted models; significance analysis; temperature distribution

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1. Introduction

Spontaneous combustion of coal gangue, which can cause wildfires, is one of the serious threats to global coal mining areas. Coal gangue is a kind of black argillaceous rock with high ash content, low carbon content, and low calorific value, which is harder than coal. The ash content is 40~50% or more, the carbon content is 10~20%, and the calorific value is as high as 1500~4700 kJ/kg. The emission of coal gangue accounts for about 15~20% of coal production; in the long-term stacking state, it spontaneous combustion often occurs [1–6]. China, India, the United States, Indonesia, Australia, and Russia are the major countries of coal production and consumption. The spontaneous combustion of coal gangue releases a lot of harmful gas, which affects the air quality around mining areas [7–9]. When the combustion exothermic reaction speed is greater than the heat dissipation speed, heat accumulation occurs, and the generated heat and gas rapidly gather in the relatively sealed gangue dump, resulting in the explosion phenomenon, directly endangering the nearby construction facilities and personal safety [10,11].The prevention and control of spontaneous combustion of coal gangue is generally caused by combustible materials, oxygen isolation, and the destruction of heat storage conditions [12,13]. At present, globally common methods include a grouting glue injection, spraying a chemical inhibitor, digging the fire source, a loess covering, water treatment, extinguishing with inert gas, and leveling compaction. However, due to the difficulty of heat transfer from the inside of the gangue dump, the gangue dump still reignites in the long run. Therefore, it is an important research topic in the field of global coal gangue dump treatment technology to strengthen the internal heat transfer process through economic and rapid technical means.

At present, the management of gangue spontaneous combustion is mainly carried out by means of oxygen isolation. In this study, a heat pipe (HP) is used to reduce the internal temperature from the perspective of heat transfer. A heat pipe (HP) is a highly efficient heat transfer and heat dissipation element. Its main principle is to use the working medium to absorb and release latent heat of vaporization to transfer heat. The thermal resistance is very small. It can transfer large amounts of heat under small temperature differences in a unique way to achieve the abnormal heat transfer effect. It has high thermal conductivity, strong adaptability to the environment, etc., and it is flexible and convenient to use. In 1965, the author of the Los Alamos laboratory established a complete theory of heat management. At present, the HP technology has been used to protect frozen soil subgrade, grain stored at low temperatures, desertification control, and oil and gas exploitation, and has achieved good results [14–19]. Since 2014, research on the suppression of the spontaneous combustion of coal using an HP has increased gradually. Schmidt et al. [20] tested the cooling effect of a single HP on the fire zone in the fire area of the Wuda Coal field. The temperature of the measuring point at 1.5m away from the HP was observed in June from 270 °C to 250 °C. Qurui [21] proposed the average cooling per hour to evaluate the cooling effect of an HP on coal stack, and pointed out that reducing the arrangement spacing, increasing insertion depth, and reducing the arrangement angle can improve the cooling capacity of the hot rod; Zhang Yaping et al. [22] analyzed self-contained coal by an HP under different arrangement parameters by changing the layout mode of the HP. The relationship between the cooling rate of the high-temperature heat source point and the liquid filling rate of the HP was established by Wang Liwei [23]. It was found that the cooling capacity of the HP was the best when the liquid filling rate was 40%. Chen Qinghua et al. [24] pointed out that the HP was affected by the internal gravity and gas–liquid shear force. Fluent simulation results show that the cooling effect was more significant when the inclination angle was 60°. Deng Jun et al. [25–28] also carried out a large number of experiments on heat transfer and cooling of an HP for coal spontaneous combustion, and studied the influence of the HP on the temperature field distribution of the coal pile by means of experiments and simulation. The above research shows that the high heat transfer characteristics of an HP can effectively restrain the heat transfer of coal spontaneous combustion.

However, there is no research on the application of the HP in the treatment of coal gangue spontaneous combustion, and the cooling effect of the HP on the spontaneous combustion area of the coal gangue dumps, and the distribution of the internal horizontal and vertical temperature under the action of the HP are not clear. The treatment of coal gangue spontaneous combustion cannot be delayed. Therefore, through a wireless temperature data collection and transmission cloud platform system, the authors have established a fitting model of shallow to deep temperatures and studied the cooling effect of the HP on different temperature areas of the coal gangue yard in Yangquan Yinying Coal Mine, to provide guidance for using an HP in the field of prevention and control of spontaneous coal gangue combustion.

2. Materials and Methods

2.1. Overview of the Study Area

The Yinying Coal Mine in Yangquan City of Shanxi Province is located 11.5 km to the northwest of Yangquan City. The industrial site of the mine is located in the gunpowder ditch about 1.5 km north of Yinying town. The main coal seam is No.15 coal. At present, the annual production design capacity and washing capacity has reached 2.4 million tons, and the output of gangue is about 400,000 tons/year. The gangue dump of Yinying Coal Mine studied in this paper has been accumulating gangue since 1994. It is located on the east side of the industrial site. All the gangues are layered from the bottom of the upper slope to the top. The 8 m-high gangue is divided into one layer, which is divided into one, two and three platforms (as shown in Figure 1), covering an area of about 16.3 hm^2. In 2006, the first spontaneous combustion occurred in the gangue dump, and then the surface of the gangue was covered with about 0.5 m loess layer, and greening measures were taken. In 2018, the area is returning to about 2600 m^2, causing the decline of vegetation on the surface. The site survey found that the surface of the gangue dump has obvious signs of fire, sometimes smoke, and you can smell a strong irritating smell, indicating that spontaneous combustion is still continuing.

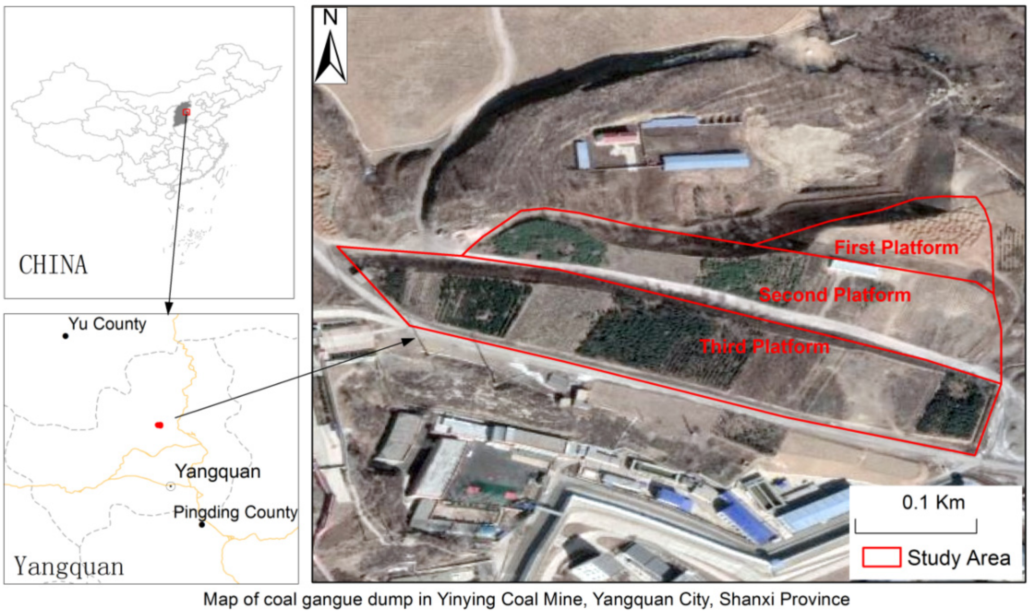

Figure 1. Location map of the study area.

2.2. Working Principle of the HP

The HP is a high-efficiency heat conduction device made of a carbon seamless steel pipe. The inner hollow is sealed with an inorganic medium, and has a unique one-way heat conduction performance. It is a phase-change cooling technology based on the evaporation and condensation of the liquid working medium, which removes large amounts of heat [29,30].

The total length of the HP is 5 m and the pipe diameter is 76 mm. The HP can be divided into two sections: the condensation section and the evaporation section (as shown in Figure 2). During the operation of the HP, the internal working medium absorbs heat through the pipe wall of the condensation section, which evaporates in the condensation section under the action of the small pressure difference between the evaporation section and the condensation section. The working medium contacts the cooler pipe wall in the condensation section, releases the latent heat of vaporization and condenses into a liquid. Under the action of gravity, the working medium flows back to the evaporation section along the pipe wall to complete the whole heat transfer cycle process. The heat source in the coal gangue dumps can be transmitted to the atmosphere continuously, and the heat loss in the high-temperature area inside it can be accelerated to achieve the purpose of cooling.

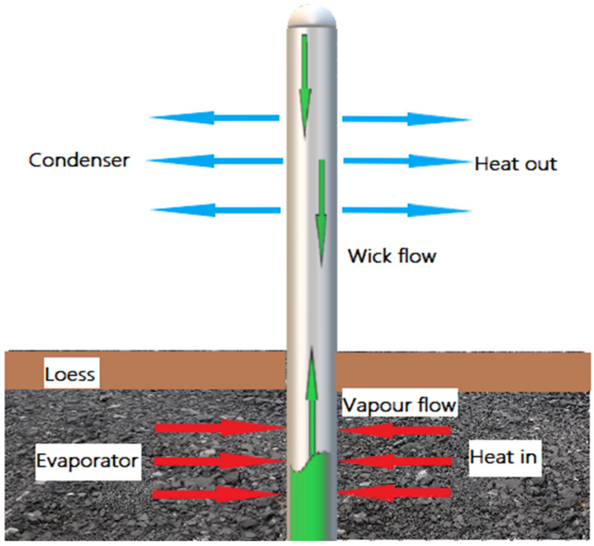

Figure 2. Working principle of the HP.

2.3. Experimental Scheme

Three groups of single tube tests were carried out in a relatively high-temperature area, medium-temperature area and low-temperature area of the gangue dump in Yinying Coal Mine. An HP and several temperature measuring tubes were installed in three temperature zones, and a 3 m-deep temperature measuring tube was installed in the low-temperature zone as the control group. Considering that the external temperature affects the heat dissipation efficiency of the HP, in order to study the inhibiting effect of the HP on gangue spontaneous combustion better, the external temperature time chosen for this test section is higher, from 13 May 2020 to 13 August 2020. This test first measured the internal temperature of the gangue field and selected the self-ignition point, the fast oxidation point, and the slow oxidation point as the installation site for the three HPs in this test. The temperature difference between this location and the surrounding area is small.

The HP was embedded in the coal gangue dump by first drilling and then inserting the tubes. The length of the HP is 5 m, its buried depth is 3.5 m, and its length is 1.5 m in the air. Wireless transmission K-type high-temperature thermocouple (armored) temperature-measuring equipment is installed at 1, 2, and 3 m along the 120° direction around the HP. The collected data are received from lora4g gateway, processed by the SaaS cloud service platform, and transmitted to a mobile phone and PC display terminal (as shown in Figure 3), so as to monitor the field temperature test data in real time. Figure 4 illustrates the arrangement of HP201 and its temperature-measuring points. According to the situation of the coal gangue dump, temperature monitoring was carried out in three groups of single pipe experiments areas to study the response of the internal temperature field of the coal gangue dump to the HP.

2.4. Initial Temperature

According to the statistics of the initial temperature of the three groups of single-tube test areas, the temperature of the HP122 test area is the lowest, and the highest temperature is at T204-8, which reaches 169.2 °C (as seen in Table 1). The temperature of 1~5 m is below 90 °C, and the temperature of 6 and 7 m is 96.5 °C and 105.6 °C, respectively, which starts to accelerate oxidation. The temperature of the HP201 test area is above 90 °C, and the temperature of 1 m and 2 m underground is the rapid oxidation in the chemical zone; the temperature at 3 m underground reaches above 350 °C, and the temperature at 5 m underground reaches the highest. In the HP168 test zone, the temperature at 1m is below 90 °C, the temperature at 2 m and 3 m is the rapid oxidation zone, the temperature at T304-4 reaches 432.5 °C, and the temperature at T304-7 reaches the highest, 572.5 °C, followed by T304-8, 544.2 °C.

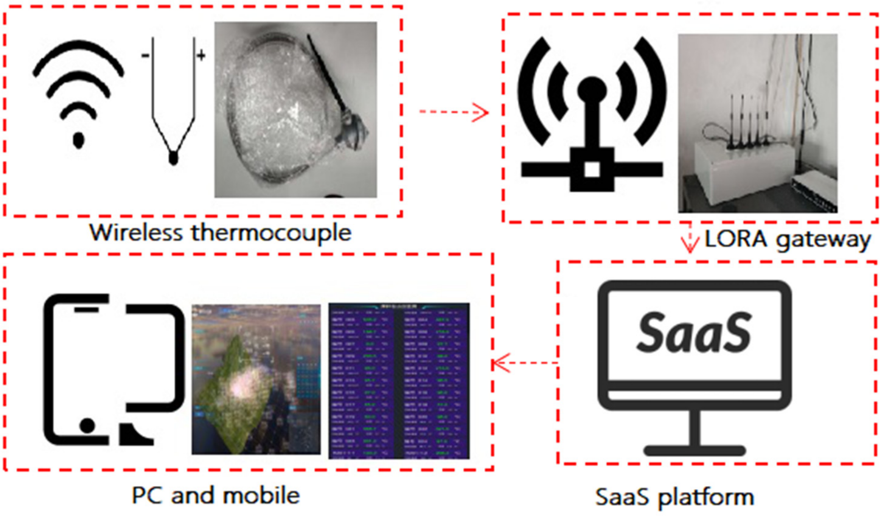

Figure 3. Data acquisition and transmission system.

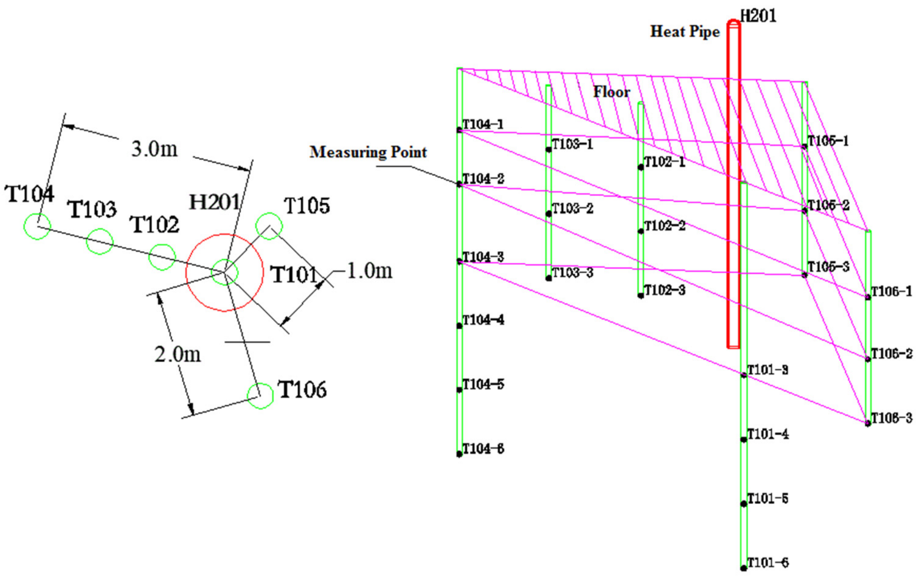

Figure 4. The first platform HP and temperature measurement point layout.

Table 1. Initial temperature data.

No. of HP	No. of Measuring Point	Depth/m							
		1	2	3	4	5	6	7	8
HP201	T101			383.5 °C	453 °C	485 °C	493.7 °C		
	T102	104.7 °C	244 °C	373.7 °C					
	T103	122.2 °C	260 °C	394 °C					
	T104	106.2 °C	297.4 °C	398.2 °C	471.2 °C	488.5 °C	485.2 °C		
	T105	122.2 °C	246.7 °C	404.7 °C					
	T106	112.2 °C	287.3 °C	415 °C					
HP122	T201			64 °C	79.5 °C	88 °C	98 °C		
	T202	47.7 °C	65 °C	74.5 °C					
	T203	49.7 °C	77.2 °C	74.2 °C					
	T204	48 °C	74 °C	71.2 °C	76 °C	87.2 °C	93.2 °C	99.7 °C	165 °C
	T205	46.7 °C	63.5 °C	71.5 °C					
	T206	60.7 °C	79 °C	81 °C					

Table 1. *Cont.*

No. of HP	No. of Measuring Point	Depth/m							
		1	2	3	4	5	6	7	8
HP168	T301			260.7 °C	442.7 °C	528.7 °C	550.2 °C	573 °C	545 °C
	T302	84.5 °C	141.7 °C	254.5 °C					
	T303	94.2 °C	157.5 °C	251 °C					
	T304	101.7 °C	156.5 °C	262 °C					
	T305	92 °C	145.7 °C	238 °C					
	T306	101.2 °C	175.5 °C	298.2 °C					

2.5. Fitting the Model

Using the temperature at 1m as the horizontal axis and the temperature at the rest of the depth as the vertical coordinate, a scatter plot was drawn and the relationship between the two was inferred from the graphical features to largely satisfy a quadratic or logarithmic function, and the least squares method was used to fit the data curve, while a goodness-of-fit test was carried out. The correlation coefficient R^2 is used to judge the fitting effect; the closer R^2 is to 1, the better the fitting effect, and the expression is:

$$R^2 = 1 - \frac{\sum(y-\hat{y})^2}{\sum(y-\overline{y})^2} \tag{1}$$

where R^2 is the correlation coefficient, and y is the 2 m, 3 m, 4 m, and 5 m depth temperature.

3. Results and Discussion

3.1. The Relationship between Shallow and Deep Temperatures

In order to understand the law of deep gangue temperature distribution, the least squares method was used to establish a fitting model of the effect of the shallow temperature of the gangue dump on the deep temperature, and the goodness-of-fit was judged by the size of the correlation coefficient; finally, the significance test was carried out by analysis of variance.

The 1 m and 2 m temperature fitting models are shown in Figure 5. By comparison, the quadratic model had a higher correlation coefficient R^2 and a better fit, followed by the quadratic and logarithmic fits for the 1 m temperature and the rest of the depth, respectively, and the results are shown in Table 2.

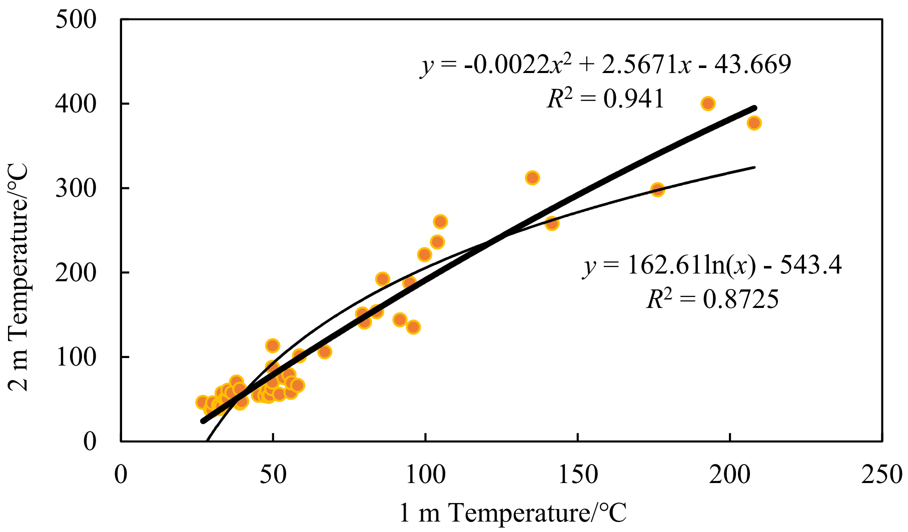

Figure 5. Fitting diagram of temperature.

Table 2. Temperature fitting results table.

Fitted Models	Quadratic Fitting Equations	Logarithmic Fitting Equations
1 m and 2 m	y = −0.0022x^2 + 2.5671x − 43.669 (R^2 = 0.941)	y = 162.61ln(x) − 543.4 (R^2 = 0.8725)
1 m and 3 m	y = −0.0089x^2 + 4.7838x − 78.533 (R^2 = 0.9141)	y = 238.25ln(x) − 778.17 (R^2 = 0.8909)
1 m and 4 m	y = −0.0201x^2 + 7.9185x − 164.62 (R^2 = 0.9646)	y = 292.7ln(x) − 945.83 (R^2 = 0.9437)
1 m and 5 m	y = −0.0212x^2 + 8.1371x − 143.95 (R^2 = 0.9699)	y = 293.32ln(x) − 920.61 (R^2 = 0.953)
1 m and 6 m	y = −0.0268x^2 + 9.5022x − 150.73 (R^2 = 0.9511)	y = 308.68ln(x) − 939.78 (R^2 = 0.9364)

As shown in Table 2, the R^2 of the quadratic model for the 1 m temperature on the 2~6 m temperatures is greater than the R^2 of the logarithmic model, so the quadratic fit is better.

3.2. Model Significance Analysis

Significance analysis is used to test the degree of merit of the effect of the regression equation. According to the theory of statistical analysis, let Xm = xm, a quadratic non-linear regression can be regarded as a binary linear regression, and then the significance analysis of this regression equation can be tested using the binary linear regression test statistic.

The mathematical model expressions are:

$$\begin{gathered} Y = a_0 + a_1 x + a_2 x^2 + \varepsilon \\ \varepsilon \sim N\left(0, \sigma^2\right) \end{gathered} \tag{2}$$

where ε is the error term.

The regression equation is:

$$\hat{y} = \hat{a}_0 + \hat{a}_1 x + \hat{a}_2 x^2 \tag{3}$$

Assumption H0: $a_0 = a_1 = a_2 = 0$; alternative assumption H1: at least one $a_i \neq 0$ (i =1,2)

The test statistic is:

$$F = \frac{Q_R/2}{Q_E/(n-3)} \sim F(2, n-3) \tag{4}$$

$$Q_E = \sum_{i=1}^{n} \left(Y_i - \hat{Y}_i\right) \tag{5}$$

where Q_R is the sum of squared deviations; Q_E is the sum of squared residuals.

In this paper, the significance level α was set at 0.01 and the critical value of $F_{0.01}$ (2, $n-3$) of the F distribution was compared with the magnitude of the calculated value of F. If: the test statistic $F \geq F_{0.01}(2, n-3)$, the original hypothesis was rejected and the regression equation was significant, and vice versa, it was not significant. The results of the significance tests are shown in Table 3.

Table 3. Results of significance test.

Fitted Models	Freedoms	F-Value	F Critical Value
1 m and 2 m	34	7.825	5.29
1 m and 3 m	29	6.438	5.42
1 m and 4 m	8	11.312	8.65
1 m and 5 m	5	15.496	13.3
1 m and 6 m	6	12.852	10.9

As shown in Table 3, the F-values are all significantly greater than the F critical value at a significance level of 0.01, so the quadratic regression model regression is significant and can be used as an expression for the shallow temperature to estimate the deep temperature.

3.3. Effect of the HP on Gangue Dumps

Taking the HP122 group test as an example, the control group was compared with 3 m depth and without the HP, and the temperature change diagram was created from HP installation to 700 h, as shown in Figure 6.

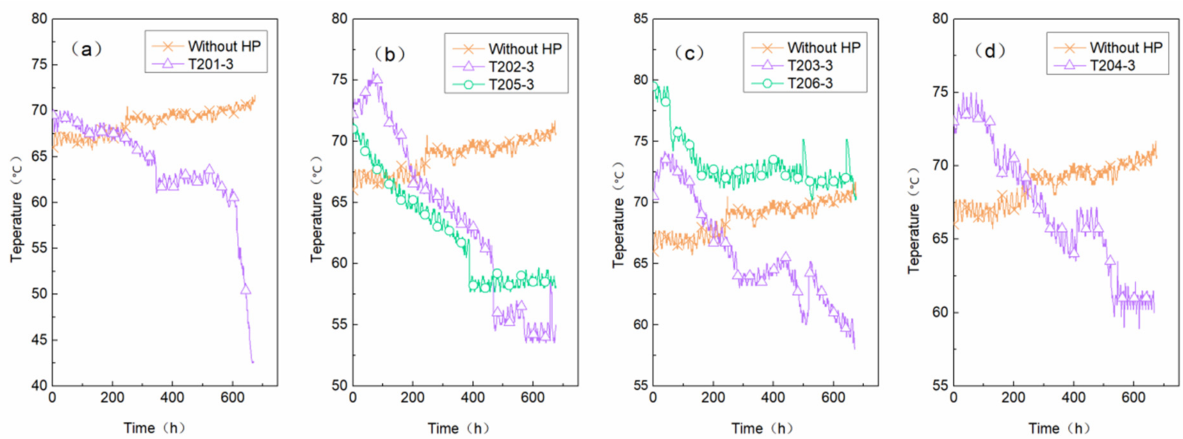

Figure 6. Comparison of the temperature with and without an HP. (**a**–**d**) show the temperature changes at the detection points at 0m, 1m, 2m and 3m from the HP compared to the without HP.

It can be seen in Figure 6a–d that the existence of the HP has a great influence on the internal temperature change of the coal gangue dump. In the case of no HP, the temperature of the gangue dump at this location increases from 66 °C to 71.7 °C within 700 h, and the temperature rises by 5.7 °C, with a large temperature change slope, while the temperature at T201-3, which is 0m away from the HP, decreases from 69.5 °C to 42.5 °C within 700 h, and the temperature is in a state of continuous decline. The temperature of T202-3 in Figure 6b rises from 72.2 °C to 74.5 °C at a horizontal distance of 1m from the HP, and then continues to drop to 55 °C. After 100 h, the temperature of T205-3 continues to drop by 13.5 °C. The temperature of at T203-3 temperature measuring point in Figure 6c fluctuates from 70.5 °C to 74.2 °C at a distance of 2 m from the HP horizontally, and then decreases continuously after 100 h, which indicates that the heat transfer of the HP has stabilized at this time, with a decrease of 17.7%; the temperature of T206-3 temperature measuring point in Figure 6c decreases from 79.5 °C to 70.3 °C within 700 h, with a decrease of 9.2 °C. The temperature measurement point T204-3 in Figure 6d fluctuates from 73 °C to 75 °C at 3 m away from the HP, and then continues to drop to 60 °C.

In Figure 6, it can be seen that: (1) in the low-temperature oxidation zone where the temperature of the gangue dump is below 90 °C [31–33], after the HP has been running for 700 h, the temperature is in a state of continuous decline, and the temperature change slope is large, while the temperature of the control group without the HP is in a state of continuous rise. (2) It takes about 100 h for the HP to reach a stable heat transfer state. (3) The HP heat transfer has a certain disturbing effect on the temperature of the coal gangue dump, and accelerates its heat dissipation. The average cooling range at 3 m underground is 21.44%, which effectively reduces the internal temperature of the study area. (4) It can be considered that the effective radius of the HP is 3 m in the low-temperature oxidation zone below the critical temperature point (80~90 °C).

3.4. Horizontal Temperature Variation

In order to study the horizontal temperature distribution characteristics of the gangue dump under the action of the HP, taking the HP201 test as an example and using the temperature data series collected by each temperature measurement point in the test, from 13 May 2020 to 13 August 2020, the contour map of horizontal temperature distribution at different depths inside the gangue dump before and after installing the HP was drawn, as shown in Figure 7.

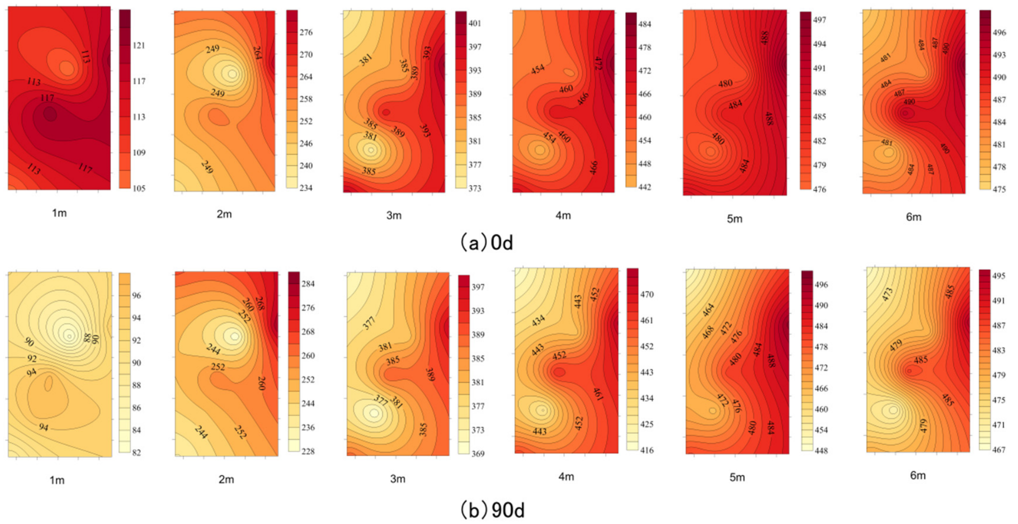

Figure 7. Horizontal temperature distribution inside the coal gangue dump of HP201.

Figure 7a shows the initial 1m-6m temperature distribution of HP201 and Figure 7b shows the 1–6 m temperature distribution after 90 days. It can be seen that 1m-6m temperatures all show varying degrees of cooling after 90 days. (1) The overall distribution of temperature in the study area is that the temperature in the southeast is higher than that in the northwest. (2) The internal temperature distribution of the gangue increases from top to bottom, and the temperature distribution of each layer is uniform without a temperature concentration point. (3) The temperature at 5 and 6 m is the highest because the heat at 1 and 2 m away from the ground level can be transferred externally, and a part of the heat is dissipated by itself, and the temperature at larger depths does not easily transfer to outside of the gangue, which leads to the formation of heat storage area.

Overall, the HP makes the temperature distribution in the coal gangue dump more uneven, which accelerates the heat dissipation rate and has a high efficiency of heat conduction.

3.5. Vertical Temperature Variation

In order to study the vertical temperature distribution characteristics of the coal gangue dump in Yinying Coal Mine under the action of the HP, taking HP201 test as an example, the vertical temperature distribution of the measuring points is shown in Figure 8.

Figure 8a–f represent the vertical temperature distribution in the gangue dump of HP201 before and after 90 days from 1m-6m. It can be seen that the vertical temperature distribution pattern was consistent from 1m-6m before and after 90 days. (1) With the increase in depth, the overall temperature has an upward trend: the minimum temperature is 104.7 °C, the maximum temperature is 493.7 °C, and the temperature at 3 m depth reaches 320 °C, and spontaneous combustion begins [34]. (2) The maximum temperature difference is 191.2 °C at a depth of 1 and 2 m, and the minimum temperature difference is 3.2 °C at a depth of 5 and 6 m. This is because, after spontaneous gangue combustion, part of the heat conducts upward, making the surface temperature rise, and part of the heat conducts downward, making the deep gangue temperature rise. The surface easily transfers heat via convection with the outside air and dissipates heat; after a period of time, the surface temperature drops, and the temperature difference between the 1 and 2 m layers becomes larger. At this time, the deep temperature is greater than the shallow temperature, and the internal temperature of the gangue starts to rise from the deep to the surface. The temperature difference between 5 and 6 m layers becomes smaller. (3) The trend in vertical temperature at different temperature-measuring points is basically the same, which reflects the common characteristics of the relationship between internal temperature and depth of the coal gangue dumps to a certain extent.

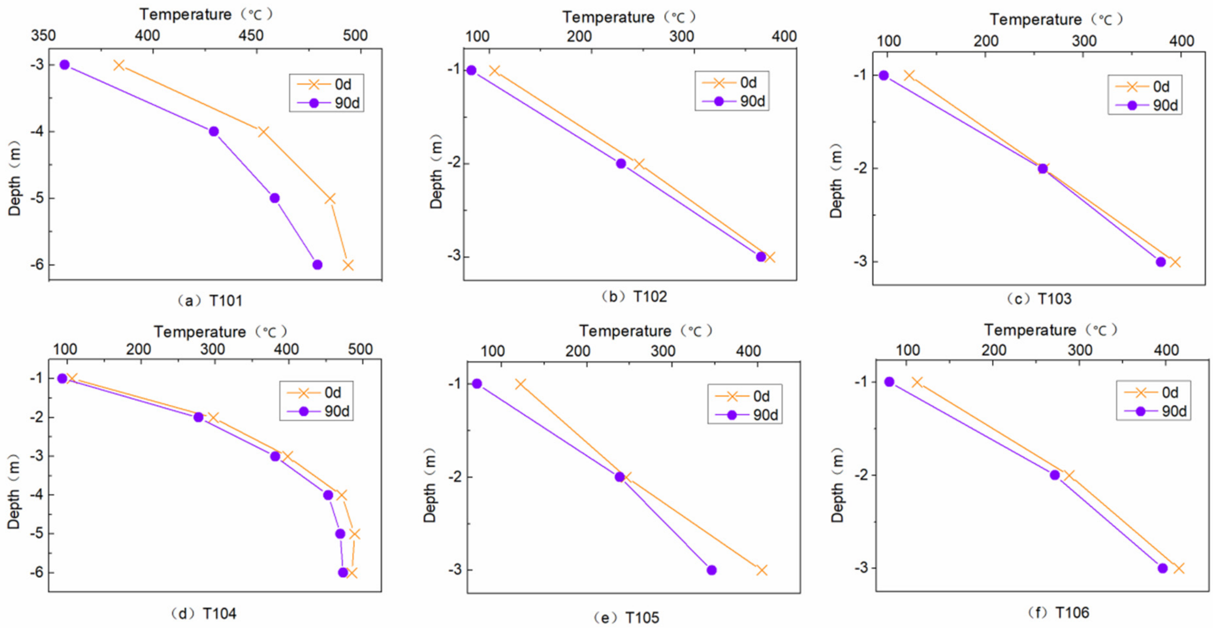

Figure 8. Vertical temperature distribution inside the coal gangue dump of HP201.

After 90 days of continuous operation of the HP, the temperature of the temperature-measuring points at 0, 1, 2, and 3 m away from the HP decreases, and the closer the distance is, the better the cooling effect is. This is due to the HP gradually absorbing the internal heat of the gangue through heat radiation and heat conduction, making the temperature on the surface of the HP rise continuously and conducting the heat out. After cooling, the lowest temperature is 84.5 °C and the highest temperature is 473 °C. The cooling range of T102 and T105 is basically the same, and that of T103 and T106 is basically the same. It can be seen in Figure 8d that there is a certain cooling effect at a horizontal distance of 3 m, but the cooling effect is the worst compared with other temperature-measuring points, which indicates that the maximum controllable radius of the HP in this area is 3 m.

3.6. Maximum Cooling Range in Different Temperature Zones

The maximum cooling range of each depth in 90 days in three experimental areas under the action of the HP was compared. It can be seen in Figure 9a–d that the temperature of the three groups of test temperature-measuring points decreased in varying degrees. The results show that: (1) the effective cooling radius of the HP in the three temperature zones is 3 m, and the farther the horizontal distance of the HP is, the smaller the cooling range is. (2) The cooling range of the shallow temperature is larger than that of the deep temperature, which is due to the buried depth of the HP being 3.5 m, the working medium in the evaporation section being 1m, and the buried depth of 1 and 2 m more easily dissipating heat; the shallow temperature more easily forms heat convection with the outside world. (3) The gangue layer with a depth of 1–4 m and the temperature between 90 °C and 450 °C has the best cooling effect.

Comparing the three single-tube test groups, the HP122 group has the smallest cooling range, which is due to the low initial temperature of the temperature-measuring point of this group, which belongs to the low temperature oxidation zone. After 90 days of operation of the HP, the average cooling is 25.6 °C, and the temperature in this zone drops to a more stable range, which greatly reduces the oxidation reaction rate and prevents the possibility of rapid oxidation.

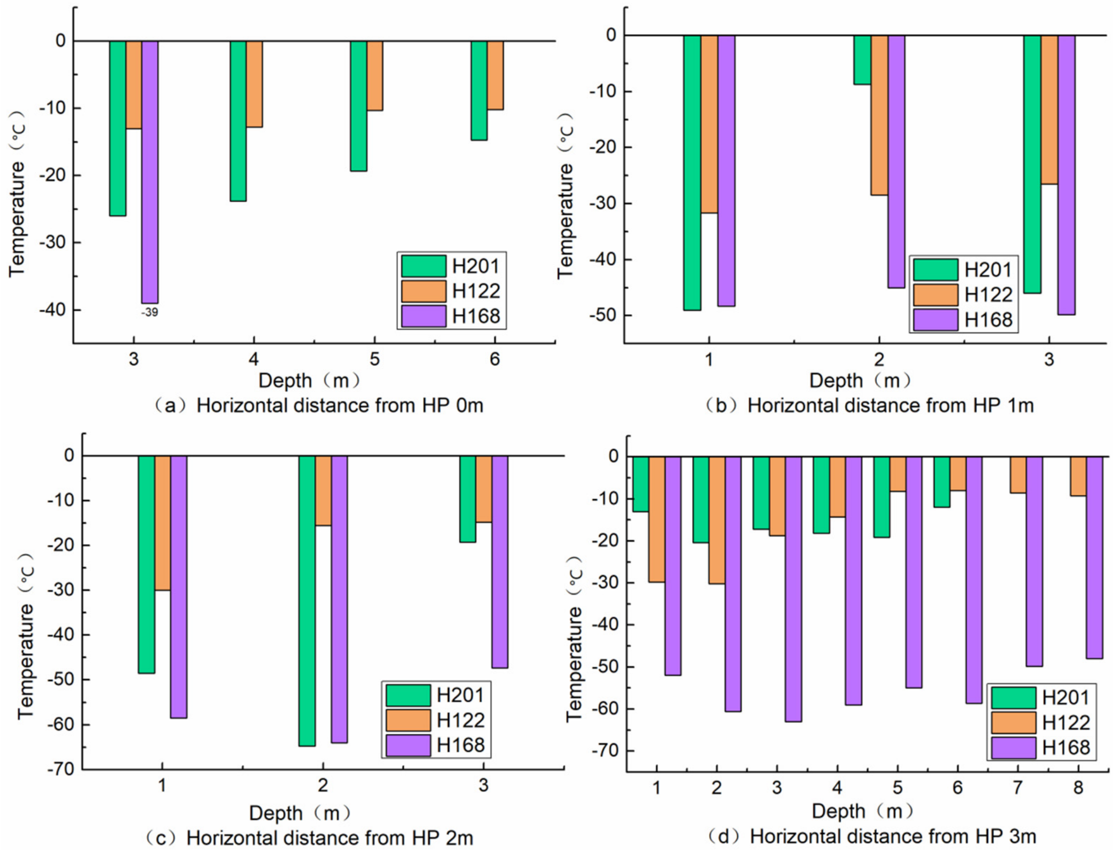

Figure 9. Temperature changes of three platforms at different depths under the action of HPs.

The initial temperature of group H168 was the highest of the three groups, reaching 573 °C, but the cooling range was the largest, which was due to the fact that a large area of the site in group H201 was hotter, and the surface vegetation was dead, and there was a distinct pungent smell when walking into the area, whereas group H168 was located in a part of the area where the temperature was lower and the vegetation was growing well, and this test was a single-tube test with a limited cooling range.

4. Conclusions

In this paper, the least squares method was used to establish the fitting model for shallow and deep temperature. The goodness-of-fit test and significance analysis were carried out to study the temperature change, horizontal and vertical temperature distribution characteristics of the gangue dump under the action of an HP, and the cooling effect of the HP on the temperature zone of the gangue dump was discussed systematically. The idea of this study is to provide a theoretical basis for the technology of HP treatment of spontaneous combustion in gangue dumps. The following main conclusions were obtained:

(1) The quadratic regression model fits better than the logarithmic function model, and the regression is significant and can be used as an empirical regression formula for the temperature between shallow and deep layers.
(2) The HP has high thermal conductivity and an obvious cooling effect on the coal gangue dump. In the low-temperature oxidation zone below 80~90 °C of the gangue dump, compared with the control group without an HP, the temperature of the HP decreased continuously after 700 h, and the HP needed a stable period of about 100 h in the early cooling period, with an average cooling range of 21.44%, while the control group without HP was in a continuous rising state, with a heating range of 8%. Under the action of the HP, the cooling range of the three single-pipe test groups is different, showing a regular change. The internal temperature drop of the coal gangue dump

is inversely proportional to the horizontal distance and directly proportional to the working time, and the control radius for the three groups of tests is 3 m.

(3) In the vertical direction, the temperature difference between the shallow layer and the deep layer is larger, and the internal temperature is proportional to the depth. The decrease is related to the spontaneous combustion, the depth of the HP, the location of the ignition point, and the temperature range. The HP mainly reduces the temperature of the gangue layer with a depth of 1~4 m. HP technology has an obvious control effect on different temperature zones of spontaneous combustion in the coal gangue dump, and can effectively improve the economy of spontaneous combustion treatment of the coal gangue dump.

The research in this paper can provide a basis for using heat pipes to cool down and extinguish fires on the spontaneous combustion gangue mountain, but there are certain problems in the research, which need further research in the future. The effect of the heat pipe model, and the effect of the group pipe arrangement density and arrangement method on cooling needs to be further studied in the future to form a more efficient arrangement scheme.

Author Contributions: This work was conducted in collaboration of all authors. N.Z., Y.Z., X.Z. and J.N. conceived and designed the experiments; N.Z., T.G. and N.Y. performed the experiments; N.Z., H.S. and L.G. analyzed the data. N.Z. wrote the paper. All authors have read and agreed to the published version of the manuscript.

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