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

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Abstract

Coal gangue in long-term accumulation will often appear spontaneous combustion phenomenon. Generally, the disaster caused by it has always been one of the serious problems threatening the health of residents in the mining area. Master the regularity of deep temperature distribution and eliminate the internal heat is an effective method to control the spontaneous combustion. In this study, using the self-developed heat pipe (HP) and intelligent cloud monitoring software, three groups of single pipe experiments were carried out in different temperature areas of the coal gangue dump in Yinying Coal Mine, to analyze the internal temperature variation under the action of HP. The results show that the temperature is obviously restrained by the HP, and the average cooling range reaches 21.44% within 700h. However, the temperature of the control group without HP continued to rise by 8%. In the three groups of experiments, the effective control radius of single HP is 3m. When the depth of gangue is 1 ~ 4m and the temperature between 90 °C ~ 450 °C, the cooling effect is the best. It revealed that the HP had a substantial effect on thermal removal and inhibited spontaneous coal gangue combustion. In addition, this paper provides a theoretical basis for the HP treatment of spontaneous combustion coal gangue dumps technology.

Background

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 ~ 4700kJ/kg. Under the long-term accumulation state, it often has spontaneous combustion¹⁻⁵. China is a big country of coal production and consumption. The emission of coal gangue accounts for about 15%~ 20% of coal production, and the annual emission is about 280 million tons⁶. According to statistics, the accidents caused by spontaneous combustion of coal gangue account for 50% of the accidents. The spontaneous combustion of gangue releases a lot of harmful gas, which affects the air quality around the mining area⁷⁻⁹. 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 dump generally starts from combustible materials, oxygen isolation and destruction of heat storage conditions^{12,13}. The commonly used methods include grouting glue injection, spraying chemical inhibitor, digging fire source, loess covering, water treatment, inert gas extinguishing and leveling compaction. However, due to the difficulty of heat transfer from the inside of the gangue dump, the gangue dump will still reignite in the long run. Therefore, it is an important research topic in the field of coal gangue dump treatment technology to strengthen the internal heat transfer process of it through economic and rapid technical means.

HP is a high efficiency 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 heat under small temperature difference in a unique heat transfer way to achieve the abnormal heat transfer effect. It has high thermal conductivity, strong adaptability to 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 recovery and transfer waste heat in the coal fire field, to protect the frozen soil subgrade, low temperature grain storage, desertification control, oil and gas exploitation, and has achieved good results¹⁴⁻¹⁸.

The high heat transfer characteristics of HP can effectively restrain the heat transfer coal gangue spontaneous combustion^{19,20}. Schmidt et al.²¹ tested the cooling effect of 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. Since 2014, the domestic research on the suppression of coal spontaneous combustion by HP has increased gradually. Qurui²² proposed the average cooling per hour to evaluate the cooling effect of HP on coal stack, 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.²³ analyzed the self-contained coal by HP under different arrangement parameters by changing the layout mode of HP. The relationship between the cooling rate of high temperature heat source point and the liquid filling rate of the HP was established by Wang Liwei²⁴. It was found that the cooling capacity of the HP was the best when the liquid filling rate was 40%. Chen Qinghua et al.²⁵ pointed out that the HP was affected by the internal gravity and gas-liquid shear force. Fluent simulation results showed that the cooling effect was more significant when the inclination angle was 60 °. Deng Jun et al.²⁶⁻²⁹ also carried out a large number of experiments on heat transfer and cooling of coal spontaneous combustion HP, and studied the influence of HP on the temperature field distribution of coal pile by means of experiment and simulation.

The existing research on the technology of HP to treat the spontaneous combustion of coal gangue dumps is mostly limited to the laboratory evaluation and research on the cooling performance of the HP. However, 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. Therefore, the author studies the cooling effect of HP in different temperature areas on the coal gangue dump in the Yangquan Yinying Coal Mine based on the HP and wireless temperature data acquisition and transmission cloud platform system, and provides guidance for the HP in the field of prevention and control of spontaneous combustion of coal gangue.

Experiment And Methodology

Experimental background. The Yinying Coal Mine in Yangquan City of Shanxi Province is located 11.5km to the northwest of Yangquan City. The industrial site of the mine is located in the gunpowder ditch about 1.5km in the 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 400000 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 8m high gangue is divided into one layer, which is divided into one, two and three platforms (as shown in Fig 1), covering an area of about 16.3hm². In 2006, the first spontaneous combustion occurred in the gangue dump, and then the surface of the gangue was covered with about 0.5m loss layer, and greening measures were taken. In 2018, the area of returning is about 2600 m², causing the decline of vegetation on the surface.

The climate of the study area is continental monsoon climate, warm temperate semi-arid climate. The climate is characterized by four distinct seasons, drought in spring, more wind and less rain; hot in summer, more rainfall; cool in autumn, humid and rainy; cold and dry in winter. The annual average temperature is 9.1 °C, the extreme minimum temperature is -20.5 °C, the extreme maximum temperature is 40 °C; January is the coldest, the average temperature is -5.9 °C, July is the hottest, the average temperature is 22.1 °C, the annual temperature range is large, the average temperature is 28.0 °C; The annual average atmospheric pressure is 907.8hpa; the annual average precipitation is 562.8mm, the annual average evaporation is 1880.1mm, which is 3.55 times of the precipitation.

Working principle of HP. The HP is a kind of high efficiency heat conduction device made of carbon seamless steel pipe. The inner hollow is sealed with inorganic medium, and has unique one-way heat conduction performance. It is a phase change cooling technology based on evaporation and condensation of liquid working medium and carrying a lot of heat^{30,31}.

The total length of the HP is 5m and the pipe diameter is 76 mm. The HP can be divided into two sections, condensation section and evaporation section (as shown in Fig2). During the operation of the HP, the internal working medium absorbs heat through the pipe wall of the condensation section, and evaporates to 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 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.

Experimental methods and process. Three groups of single tube tests were carried out in the relatively high temperature area, medium temperature area and low temperature area of the gangue dump in Yinying Coal Mine. A 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.

The HP was embedded in the coal gangue dump by drilling first and then intubation. The length of the HP is 5 m, the buried depth of it is 3.5 m, and the length of it is 1.5 m in the air. Wireless transmission K-type high temperature thermocouple (armored) temperature measuring equipment is installed at 1, 2 and 3m along the 120 ° direction around the HP. The collected data are received from lora4g gateway, processed by SaaS cloud service platform and transmitted to mobile phone and PC display terminal (as shown in Fig 3), so as to monitor the field temperature test data in real time. Fig 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 coal gangue dump to HP.

Results And Discussion

Results and discussion

Initial temperature. According to the statistics of the initial temperature of three groups of single tube test areas, the analysis of Tab 1 shows that the temperature of HP122 test area is the lowest, and the highest temperature is at T204-8, which reaches 169.2 °C. The temperature of 1~5m is below 90 °C, and the temperature of 6 and 7m is 96.5 °C and 105.6 °C respectively, which starts to accelerate oxidation; the temperature of HP201 test area is above 90 °C, and the temperature of 1m and 2m underground is rapid oxygen in the chemical zone, the temperature at 3m underground reaches above 350 °C, and the temperature at 5m and 6m underground reaches the highest; in the HP168 test zone, the temperature at 1m is below 90 °C, the temperature at 2m and 3m 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.

To sum up, the gangue in HP122 test area is in the oxidation stage, and there is no spontaneous combustion phenomenon. HP201 and HP168 test areas start spontaneous combustion at the depth of 3m and 4m respectively, and reach the highest temperature at 6m and 7m respectively. This is because the buried depth of 1 and 2m is easy

to conduct heat conduction with the external environment, and the heat is easy to dissipate. The greater the buried depth of gangue, the easier the heat is to accumulate and difficult to dissipate, resulting in higher temperature.

Comparison between HP and without HP data. Take HP122 group test as an example, compare the control group with 3m depth and without HP, draw the temperature change diagram from HP installation to 700h, as shown in Fig 5.

It can be seen from Fig. 5 (a) ~5 (d) that the existence of HP has a great influence on the internal temperature change of 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 700h, 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 700h, and the temperature is in a state of continuous decline. The temperature of T202-3 in figure (b) 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 100h, the temperature of T205-3 continues to drop by 13.5 °C. The temperature of T203-3 temperature measuring point in figure (c) fluctuates from 70.5 °C to 74.2 °C at a distance of 2m from the HP horizontally, and then decreases continuously after 100h, 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 (c) decreases from 79.5 °C to 70.3 °C within 700h, with a decrease of 9.2 °C. The temperature measurement point T204-3 in figure (d) fluctuates from 73 °C to 75 °C at 3m away from the HP, and then continues to drop to 60 °C.

To sum up, it can be seen that: (1) in the low-temperature oxidation zone where the temperature of gangue dump is below 90 °C³²⁻³⁴, after the HP has been running for 700h, the temperature is in a state of continuous decline, and the temperature change slope is large, while the temperature of the control group without HP is in a state of continuous rise. (2) It takes about 100 hours 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 the heat dissipation of it. The average cooling range at 3m 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).

Horizontal temperature variation. In order to study the horizontal temperature distribution characteristics of Gangue Mountain under the action of HP, taking HP201 test as an example, using the temperature data series collected by each temperature measurement point in the test, draw the contour map of horizontal temperature distribution in different depth inside the gangue mountain before and after installing the HP, as shown in Fig 6.

It can be seen that: (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 gangue increases from top to bottom, and the temperature distribution of each layer is uniform without temperature concentration point. (3) The temperature at 5 and 6m is the highest because the temperature at 1 and 2m away from the ground can be heat transferred with the external temperature, and a part of the heat is dissipated by itself, and the temperature in the deep is not easy to spread to the outside, which leads to the formation of heat storage area.

After 90 days of continuous operation of HP, the temperature inside the coal gangue dump at 1 ~ 6m underground decreased to varying degrees. Among them, the cooling effect of shallow depth is the most obvious, and the influence of the disturbance action of HP is also used in the depth of 5 and 6m. The heat flux has changed, which indicates that the temperature of 6m can be disturbed when the buried depth of the HP is 3.5m.

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.

Vertical temperature variation. In order to study the vertical temperature distribution characteristics of coal gangue dump in Yinying Coal Mine under the action of HP, taking HP201 test as an example, the vertical temperature distribution of measuring points is shown in Fig 7.

It can be seen that: (1) with the increase of the 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 of 3m depth reaches 320 °C, and spontaneous combustion begins³⁵. (2) The maximum temperature difference is 191.2 °C at the depth of 1 and 2m, and the minimum temperature difference is 3.2 °C at the depth of 5 and 6m. This is because, after the gangue spontaneous combustion, part of the heat conduction upward, making the surface temperature rise, part of the heat conduction downward, making the deep gangue temperature rise, and the surface is easy to have heat convection with the outside air and heat dissipation, after a period of time, the surface temperature drops, and the temperature difference between 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 from the deep to the surface. The temperature difference between 5 and 6 m layers becomes smaller. (3) The trend of 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.

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. 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 from Fig 7 (d) that there is a certain cooling effect at a horizontal distance of 3m, 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 3m.

The maximum drop in different temperature regions. The maximum cooling range of each depth in 90 days in three experimental areas under the action of HP was compared. It can be seen from Fig 8 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 3m, 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 is 3.5m, the working medium in the evaporation section is 1m, the buried depth of 1 and 2m is easier to dissipate heat; the shallow temperature is easier to form heat convection with the outside world. (3) The gangue layer with the depth of 1-4m and the temperature between 90 °C and 450 °C has the best cooling effect.

Compared with the three groups of single tube test, 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.

The initial temperature of group H168 is the highest in three groups, reaching 573 °C, and the cooling range is the largest. This is because: in a platform where group HP201 is located, the temperature in a large area is high, and the vegetation on the surface has withered, with the obvious pungent smell; in some areas of the three platforms where

group HP168 is located, the temperature is low, the vegetation growth is good, and there are relatively few high temperature concentration points; in the test area of group HP168, the temperature is 1 ~ 4m deep This test is a single tube test, which is caused by the limited cooling range.

Conclusion

In this study, the temperature change and the horizontal and vertical temperature distribution characteristics of coal gangue dump under the action of HP were studied, and the cooling effect of HP on the temperature area of coal gangue dump was systematically discussed. The idea of this study was to provide a theoretical basis for the HP treatment of spontaneous combustion coal gangue dumps technology. The following results can be found from this study:

- The HP has high thermal conductivity and obvious cooling effect on coal gangue dump. In the low-temperature oxidation zone below 80 ~ 90 °C of gangue dump, compared with the control group without HP, the temperature of the HP decreased continuously after 700h, and the HP needed a stable period of about 100h 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 HP, the cooling range of three groups of single pipe test is different, showing a regular change. The internal temperature drop of coal gangue dump is inversely proportional to the horizontal distance and directly proportional to the working time, and the control radius for three groups of tests is 3m.
- 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 and the temperature range. The HP mainly reduces the temperature of the gangue layer with the depth of 1~4m.
- HP technology has an obvious control effect on different temperature zones of spontaneous combustion coal gangue dump, and can effectively improve the economy of spontaneous combustion treatment of coal gangue dump.

However, there are still some shortcomings in the study, such as the cooling effect of single HP is not as good as that of group pipes, so the optimal arrangement of HPs in different temperature zones of spontaneous combustion coal gangue dump can be further studied.

Declarations

Author Contributions

This work was conducted in collaboration of all authors. N.Z., Y.B.Z. and J.R.N. conceived and designed the experiments; N.Z. and Z.G.W., T.G. performed the experiments; N.Z. and H.S. analyzed the data. N.Z. and Y.B.Z. wrote the paper. All authors reviewed the manuscript.

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Tables

Tab. 1 Layout plan of temperature measuring tube

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					
HP168	T301			260.7°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	442.7°C	528.7°C	550.2°C	573°C	545°C
	T305	92°C	145.7°C	238°C					
	T306	101.2°C	175.5°C	298.2°C					

Figures

Figure 1

The location of study area

Figure 2

Schematic diagram of the working principle of the HP

Figure 3

Data acquisition and transmission system

Figure 4

The first platform HP and temperature measurement point layout

Figure 5

Comparison of the temperature with and without HP

Figure 6

Horizontal temperature distribution inside coal gangue dump of HP201

Figure 7

Vertical temperature distribution inside coal gangue dump of HP201

Figure 8

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