fire

MDPI

Article

Research on the Combustion Characteristics of Coal Piles and the Fire Risks of Closed Coal Bunkers

Lihong Zhao [1], Ping Fang [1], Zhenhua Wang [2], Jinlong Zhao [2,*] and Niqi Xiao [1]

1 Institute of Building Fire Research, China Academy of Building Research, Beijing 100013, China
2 School of Emergency Management and Safety Engineering, China University of Mining and Technology—Beijing, Beijing 100084, China
* Correspondence: zhaojinlong@cumtb.edu.cn

Abstract: Closed coal bunkers emerged as a novel form of coal storage for coal-fired power stations. Nevertheless, heat builds continually in the storage process because of the constant oxidation of coal and combined with the impact of a confined coal bunker environment, it is difficult for heat to dissipate, resulting in frequent coal bunker fires. Consequently, research on coal pile combustion characteristics is crucial to the design of coal bunker safety. The experimental platform was set up in this study to conduct combustion tests of various specifications, and the burning rate, flame height, flame temperature, and heat radiation flux were analyzed to identify the critical parameters impacting coal bunker safety. First, the maximum burning rate of coal heaps during steady burning was calculated, improving coal pile combustion theory and providing guidance for coal bunker design. Second, the maximum flame height was determined, which can provide an important design guide for coal bunker height designs. In addition, it was discovered that high temperatures in flames, smoke, and smoldering coal might cause coal bunker buildings to collapse, so future designs should strengthen coal bunker fire resistance and keep the coal pile away from the load-bearing structures to prevent collapse from excessive temperatures. Moreover, the diameter of coal piles has an influence on the heat flow. For this reason, a coal bunker's design must consider the coal pile's fire separation distance from the coal bunker and avoid large coal piles. Consequently, the study gives recommendations and support for planning coal bunker safety and enriches experimental data for coal pile fires.

Keywords: coal bunker; burning rate; flame height; flame temperature; heat radiation flux

Citation: Zhao, L.; Fang, P.; Wang, Z.; Zhao, J.; Xiao, N. Research on the Combustion Characteristics of Coal Piles and the Fire Risks of Closed Coal Bunkers. *Fire* **2023**, *6*, 123. https://doi.org/10.3390/fire6030123

Academic Editor: Ali Cemal Benim

Received: 24 February 2023
Revised: 15 March 2023
Accepted: 15 March 2023
Published: 16 March 2023

1. Introduction

Coal, one of the world's most important sources of electricity, is consumed in vast quantities due to the increase in global energy demands. In recent years, approximately 40% of the world's electricity has been generated by burning coal. This is particularly true for South Africa, China, Poland, Australia, India, and other countries where more than two thirds of their electricity is currently generated from burning coal [1]. According to official figures, China produced 4.126 billion tons of coal in 2021, accounting for 50.5% of all international production and ranking first in the world. The most common classifications for coal bunkers are the sealed type, the semi-sealed type, and the open type. In response to national environmental protection rules, the development of sealed coal bunkers has accelerated, making coal bunker safety crucial to the everyday operations of the whole power plant. Nevertheless, because of continuous oxidation, coals accumulate heat during storage, and a coal bunker is a relatively confined environment with just two outputs at the top and bottom, thus the heat is not easily dispersed externally leading the temperature of the coal body to gradually rise. Generally, the height of a coal bunker is typically between 30 and 50 m, and the "chimney effect" will manifest. The increase in coal temperature will accelerate the coal's oxidation–reduction process, which will cause the coal's temperature to continue to rise, leading to spontaneous combustion. Coal bunker fires have occurred in several nations, including China and USA [2–5]. In September 2011, a 100-ton coal bunker in South Dakota caught fire, resulting in the deaths of two firemen and the severe injury of one. In September 2020, a major fire catastrophe occurred in a Chongqing coal bunker, resulting in 16 fatalities, 42 injuries, and a loss of RMB 25.01 million. Coal bunker fires pose significant economic, environmental, and safety risks. The spontaneous burning of coal leads to the loss of valuable coal resources and the release of greenhouse-relevant gases, such as carbon dioxide and methane, as well as other poisonous chemicals that pose a danger to the health of surrounding residents. Therefore, it is valuable to research the key parameters of coal bunker safety for the daily operations of whole power plant.

Over the last few decades, scientists from throughout the world have conducted substantial studies on coal's combustion qualities [6–13]. Yang et al. [14] utilized thermogravimetry (TG) to determine the link between index gases and critical temperature under the situation of coal spontaneous combustion by examining how particle size, heating rate, and oxygen concentration impact critical temperature. Jia et al. [15] applied the temperature-programmed system (TPS) to analyze the oxygen consumption rate and CO and C_2H_4 production rules of six groups of coal samples with different particle sizes in the process of oxidation heating in order to investigate the influence of coal particle size on spontaneous combustion and oxidation characteristics of coal. Cai et al. [16] investigated the gas products and reaction parameters during low-temperature oxidation of coal with varied metamorphic levels and created a prediction model for low-temperature oxidation processes employing CO and C_2H_4. Özer Ören et al. [17] studied the 16-week oxidation behavior of lignite samples with two different particle sizes (74 and 500 microns). Stracher et al. [18] examined the kinetics and thermodynamic features of coal oxidation below 200 °C based on the change of elements during coal oxidation at low temperatures. Taraba et al. [19,20] studied the oxidation behavior of three kinds of coal in the presence of molecular oxygen under both atmospheric and subaquatic circumstances. Guo et al. [21] designed program-controlled temperature test equipment for low-temperature coal spontaneous combustion testing. In this experiment, three coal samples of various metamorphic grades were evaluated, including bituminous coal, brown coal, and anthracite. A technique is developed for forecasting temperature based on the variation of gas content in a coal sample during heating. This technique estimates the temperature range of oxidized coal in goaf. Nevertheless, the aforementioned studies only examined the effect of coal particle size and type on its combustion characteristics; few researchers have examined the effect of coal pile size on its combustion properties.

Additionally, computer simulation is currently the most common way to study how coal piles burn. Zhu et al. [22] developed a theoretical model to predict the spontaneous combustion time and location of rough coal piles in temporary coal depots by analyzing the spontaneous combustion characteristics of rough coal stockpiles using the COMSOL Multiphysics software program. Diaconu et al. [23] simulated the coal bed self-heating process based on mathematical modeling of coal stockpile self-heating. Michalec et al. [24] analyzed the spontaneous heating of coal heaps using commercial computer modeling software. Kumaran et al. [25] examined, with a one-dimensional numerical model, the key circumstances that contribute to spontaneous igniting in vast coal stockpiles with dry and moist coal layers. Akgun et al. [26] utilized a two-dimensional unsteady-state model to estimate the impacts of pile height, slope angle, particle diameter, and coal moisture content on coal stockpile spontaneous heating. Yuan et al. [27] conducted three-dimensional computational fluid dynamics (CFD) modeling to simulate spontaneous heating in a large-scale coal chamber with a forced ventilation system. Since there has not been much research done on actual fire experiments, the applicability of practical engineering in the future needs to be demonstrated further.

The current spontaneous combustion prevention and management techniques work mainly by inhibiting air from permeating through coal piles, releasing heat from coal piles, and reducing coal pile temperature. Guo et al. [20] combine a ZigBee technology and use an intrinsically safe coal bunker fire early monitoring system. By constructing a wireless sensor network, collecting data from temperature sensors and smoke sensors, then transferring the data to the host computer for data fusion, it will warn about coal bunker fires early. It improves the reliability of coal bunker fire warnings and prevents the spontaneous combustion of coal bunkers. Tan. [2] combined with the actual situation in Huanghua Port, utilized a two-dimensional geometric model of a coal bunker, selected CO_2 as the inert gas sprayed in the coal bunker, determined the position of the inert gas port of the coal bunker hopper, and studied the influence of fireproof and fire-extinguishing inerting on coal bunker inerting. Yang et al. [28] summarized the CO accident and treatment methods of the Daxing coal mine main shaft coal bunker, analyzed the main factors of the coal bunker spontaneous combustion phenomenon, combined the corresponding reasons to formulate effective prevention and treatment measures, and put forward daily management and technical measures. Zhang et al. [29] used a complex water-solution (C-WS) of sodium metasilicate nonahydrate (SMN) and polyvinyl alcohol (PVA) to wet coal particles, which reacted with CO_2 from coal oxidation and natural atmospheric air to form the cross-linked gel (SMN/PVA gel), which was examined by measuring the critical self-ignition temperature (CSIT) through the wire-mesh basket test, and test results indicated that it snugly covered the coal particle surface and inlets of micropores to prevent oxygen ingress and water emission, and thus exhibited excellent stability and compatibility. However, it is essential to highlight that coal bunker safety designs are investigated comparatively infrequently, and the national code has not yet specified its fire protection design in detail. This requires further development of both technological approaches and theories.

Therefore, this research adopted a self-built coal pile combustion experimental platform to observe the burning behaviors in the combustion experiments of different sized coal piles. Several crucial coal bunker security factors, including burning rate, flame height, flame temperature, and radiant heat flux have been analyzed. This research can enrich the fundamental experimental data on coal piles and serve as a reference for the design of coal bunker safety.

2. Materials and Methods

2.1. Coal Samples

In this research, commonly used bituminous coal was selected and acquired from the Tangshan Coal Mine in Shanxi Province, the People's Republic of China. The coal sample, with an average particle size of 3 cm, was screened, dried, and packed for future use after crushing the coal sample with a pulverizer. According to the Chinese code GB/T 212-2008, the coal sample's basic parameters, such as moisture, volatile matter, ash, and fixed carbon, were measured to find out the sample's basic composition and category. The results are listed in Table 1. Mad% is the percent of moisture, Vad% is the percent of volatile matter, Aad% is the percent of ash, and FCad% is the percent of fixed carbon. It can be seen from Table 1 that the coal sample contains less ash and moisture and is simple to ignite and burn, so it is the best choice for studying coal bunker fires caused by spontaneous combustion of coal piles.

Table 1. Industrial analysis of coal samples.

Coal Sample	Mad (%)	Vad (%)	Aad (%)	FCad (%)
Bituminous coal	7.5	28.82	1.93	61.75

2.2. Experimental Equipment

To more closely resemble the actual situation and achieve the spontaneous combustion of coal, a self-built experimental platform was constructed to simulate the process. The structural diagram of the experimental platform for coal pile combustion is provided in Figure 1. This system includes supply K-type thermocouple, two heat flow meters, a camera, a load cell, and a fire net, as well as an automatic data collection system. K-type thermocouples were chosen for use in the research because of their high sensitivity, excellent stability, high oxidation resistance, and low cost. In order to monitor the temperature change of the coal sample, the K-type thermocouples are placed vertically every 10 cm on a heat-conducting plate and inserted into the coal seam. Through investigation of some coal bunkers, it was discovered that the distance between the edge of the bunker and the nearest coal pile is 2.4 m. As a result of this discovery, a heat flow meter was positioned at a horizontal distance of 2.4 m from the center of the coal sample in order to measure the flame heat radiation heat flow. Furthermore, a camera was positioned 3.5 m from the center of the coal sample to capture the flame height. The coal sample was placed in the steel wire mesh after being pulverized into pieces in order to make it easier to ignite the coal, and then it was placed on the load cell, which was shielded from the flames by a fireproof board and has the potential to be used to evaluate the quality change that occurs in coal as it is burned. The temperature and mass loss of coal piles were monitored in real time by the automatic data collection system.

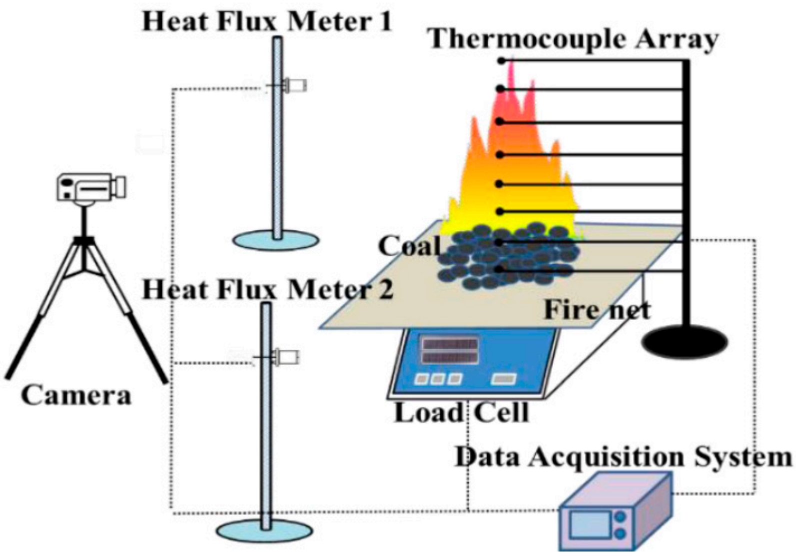


Figure 1. The testing apparatus for flame combustion of coal.

2.3. Experimental Conditions

The experiments were completed in a combustion chamber located in the Fire Protection Laboratory of the China Academy of Building Research in Beijing. The initial temperature of the experiment was 28–32 °C, and any wind effect can be ignored. Those experiments, beginning with n-heptane igniting the coal sample and ended with the flame dissipating.

2.4. Experimental Schemes Design

At present, few researchers have examined the effect of coal pile size on its combustion performance, but in practical engineering, various coal pile sizes will impact the size of the combustion scale, so this research designs nine varieties of coal pile combustion experiment schemes with various diameters and thicknesses, as shown in Table 2. Each specification was tested twice to make sure it was accurate. In later research, diameter was written as D and thickness as T.

Table 2. Coal pile combustion experimental schemes.

Schemes	Diameter (cm)	Thickness (cm)	Mass (g)
Test-1	40	2	3454.2
Test-2	40	4	3985.4
Test-3	40	6	5921.6
Test-4	60	2	6791.2
Test-5	60	4	9064.8
Test-6	60	6	11,371.0
Test-7	80	2	7656.7
Test-8	80	4	9510.7
Test-9	80	6	14,805.7

3. Results and Discussion

3.1. General Observations

Figure 2 depicts the combustion process of Test-4. There are four stages to the burning process: initial development, steady burning, decay, and smoldering. We can clearly see in the development stage that the flame represents just a small percentage of the coal pile and that it releases puffs of white smoke. When the coal pile reaches this steady state, the burning area gradually covers the whole surface, the flame radiation feedback and heat flow are nearly constant, and the rate of combustion is stabilizing. Eventually, the fuel was consumed, and the flame gradually vanished. At the conclusion of the burning cycle, all volatiles have been consumed and the flame has extinguished, ushering in the smoldering phase of combustion. Considering that the steady-burn phase accounts for the bulk of the total burning period, it is crucial to pay more attention to its properties.

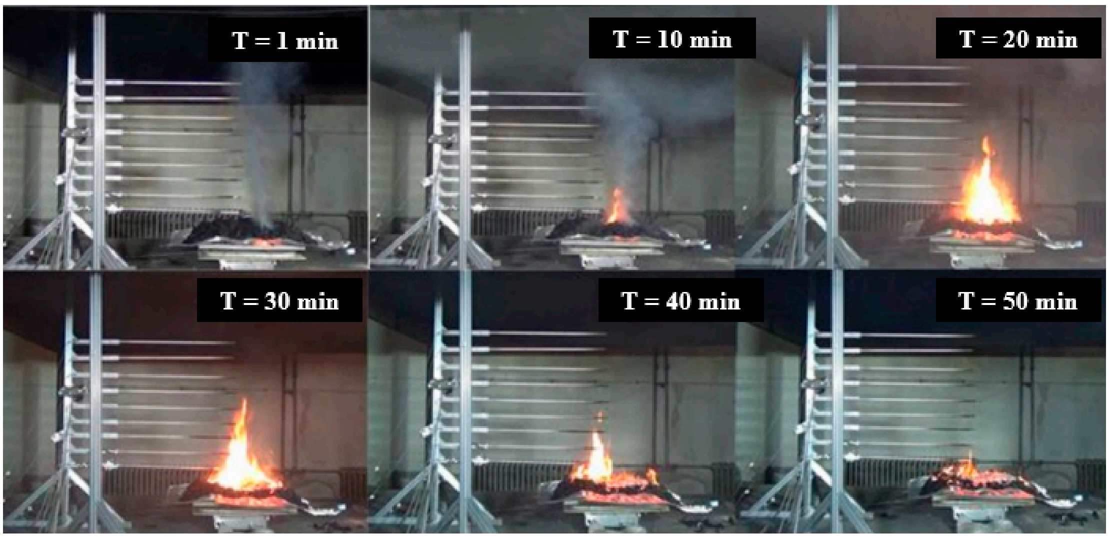


Figure 2. Burning process photographs of Test-4 at different times.

3.2. Burning Rate

The burning rate is typically used to describe the mass loss per unit time caused by fuel burning under the specified conditions (GB/T 5907.2-2015). While studying coal pile burning behaviors, burning rate is one of the most crucial factors to take into account since it directly influences heat release rate as well as flame height, radiation intensity, temperature, and other characteristics. The mass loss rate method (MLRM) [30–32] was used to calculate the burning rate in this research. Specifically, the load cell equipment is used to measure the change in weight of the fuel during combustion, and the data collector is responsible for estimating the magnitude of the change in mass during the research. The changes of burning rate from Test-1 to Test-9 are shown in Figure 3.

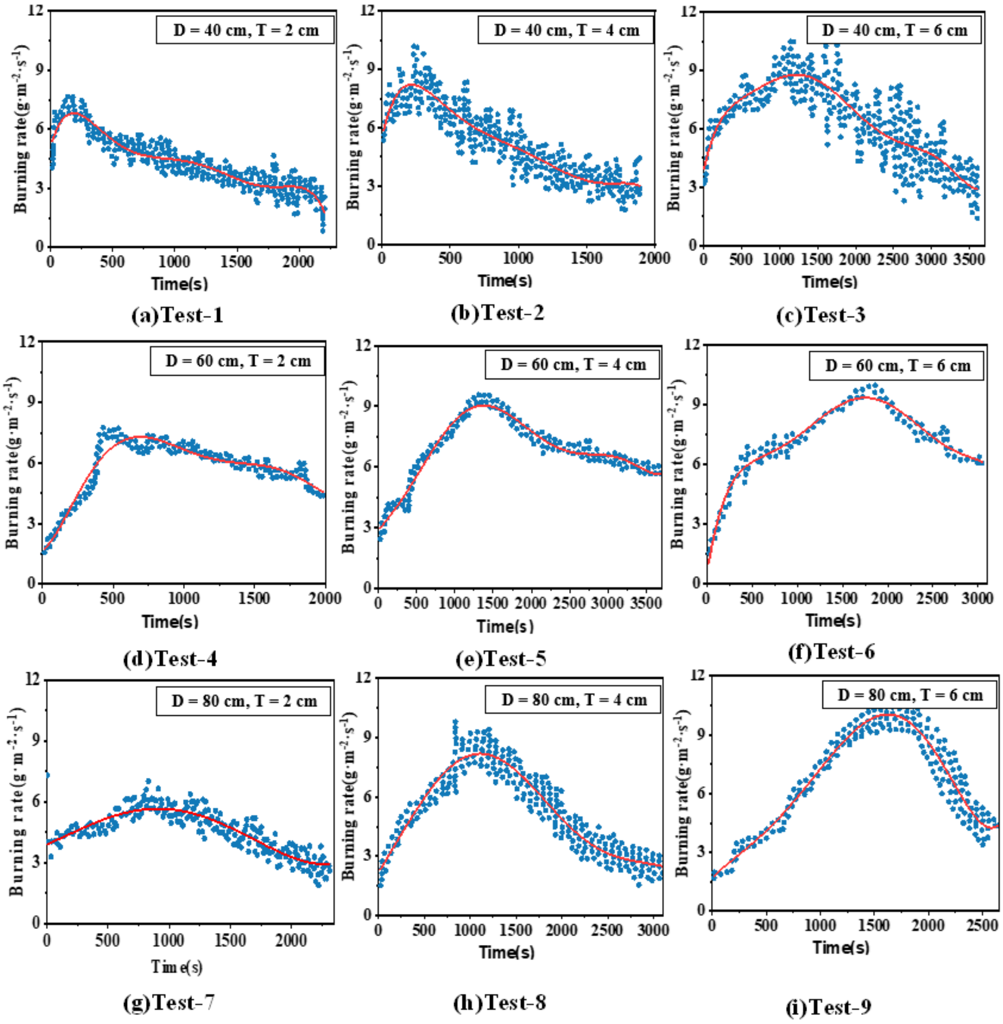


Figure 3. The changes of burning rate from Test-1 to Test-9 (where (**a**) is a coal pile of 40 cm diameter and 2 cm thickness, (**b**) is a coal pile of 40 cm diameter and 4 cm thickness, (**c**) is a coal pile of 40 cm diameter and 6 cm thickness, (**d**) is a coal pile of 60 cm diameter and 2 cm thickness, (**e**) is a coal pile of 60 cm diameter and 4 cm thickness, (**f**) is a coal pile of 60 cm diameter and 6 cm thickness, (**g**) is a coal pile of 80 cm diameter and 2 cm thickness, (**h**) is a coal pile of 80 cm diameter and 4 cm thickness, (**i**) is a coal pile of 80 cm diameter and 6 cm thickness).

Figure 3 demonstrates that the burning rate of coal piles follows the same variable trend under conditions of diverse dimensions, with the overall trend initially increasing before reducing. In addition, comparing the coal sample burning rates under different thicknesses, it is discovered that as the thickness rises from 2 cm to 4 cm, the coal sample combustion rate increases as well, but when the thickness exceeds 4 cm, the combustion rate essentially remains unchanged. The main reason for this phenomenon is that when the thickness of the coal sample exceeds a certain value, the bottom coal sample does not directly participate in the combustion and contributes very little to the maximum combustion rate. However, comparing the coal sample burning rates under different diameters, it is found that the burning rate does not increase significantly. This is primarily due to the fact that coal combustion does not produce large areas of high temperatures like conventional liquid flames. In the entirety of the coal combustion process, flame radiation feedback is relatively stable, possibly due to the interference of the pyrolysis rate with the burning rate. In this case, the burning rates were 7.5 g/(m^2s), 9 g/(m^2s), and 10 g/(m^2s) when the initial thicknesses were 2 cm, 4 cm, and 6 cm, respectively. Equation (1) can be derived from fitting the steady burning rate data with different thicknesses, and the burning rate can be calculated as 10.5 g/(m^2s). This equation can be applied to the design of coal piles. The burning rate fitting curve with different diameters is shown in Figure 4.

$$y = -0.0625x^2 + 1.125x + 5.5 \tag{1}$$

where y is the burning rate (g·m^{-2}·s^{-1}) and x is the coal pile thicknesses (cm).

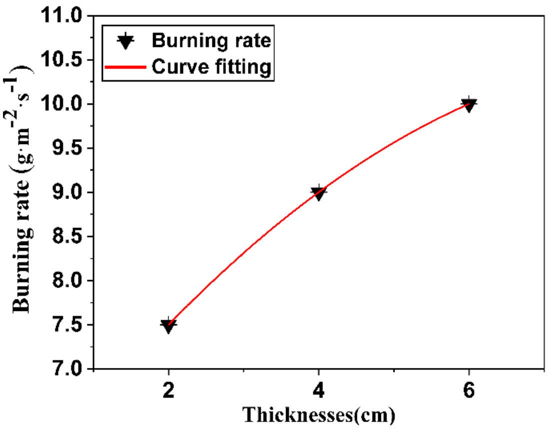


Figure 4. The burning rate fitting curve with different thicknesses.

3.3. Flame Height

The flame height has a direct effect on the flame's range and has an effect on the dispersion of radiation surrounding the flame. As a result, the research on the coal flame's height is of the highest significance with respect to the design of the height of the coal bunker. To further obtain real-time flame heights, the method of identifying RGB pixels [33,34] was employed (R > 240, G > 140, and B > 35) to outline the flame, and the results are shown in Figure 5.

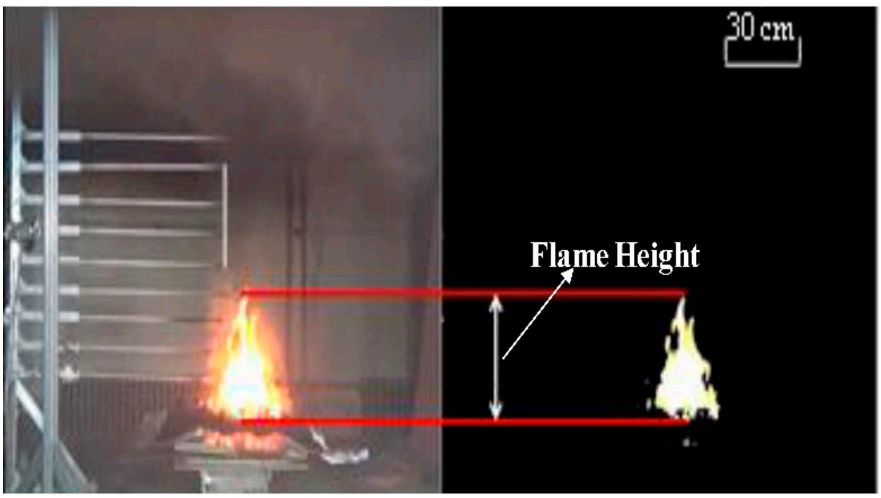


Figure 5. Comparison between pictures of flame height before and after processing.

In the flame height influence factor analysis, Test-4 to Test-6 were used to assess the effect of fuel thickness on flame height, whereas Test-2, Test-5, and Test-8 were used to determine the relationship between flame height and diameter. The value of the flame height can be obtained by applying RGB pixel recognition to the recorded video, as shown in Figures 6 and 7.

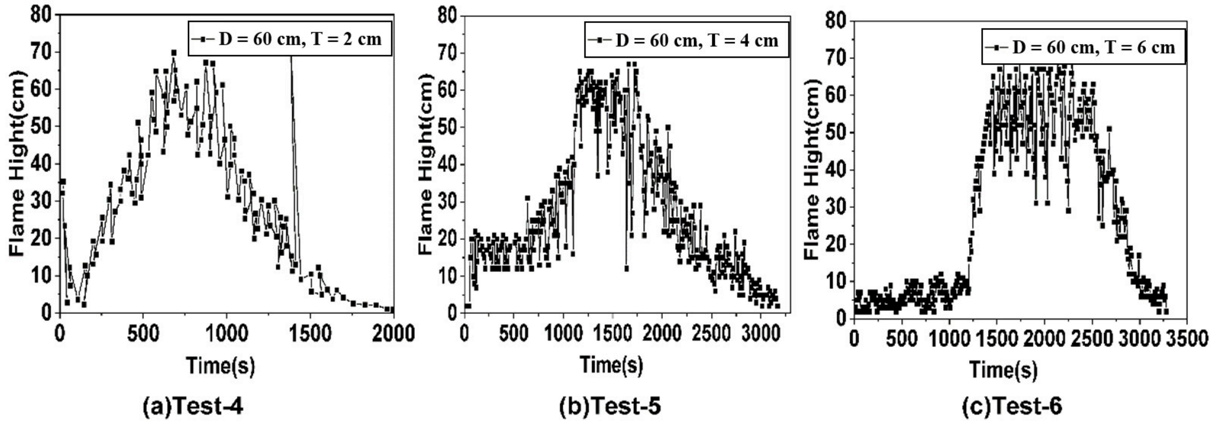


Figure 6. The flame height changes from Test-4 to Test-6 (where (**a**) is a coal pile of 60 cm diameter and 2 cm thickness, (**b**) is a coal pile of 60 cm diameter and 4 cm thickness, (**c**) is a coal pile of 60 cm diameter and 6 cm thickness).

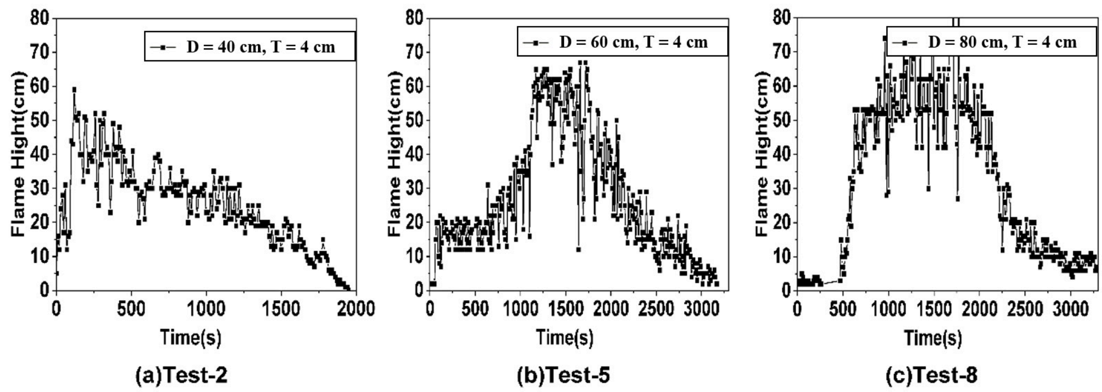


Figure 7. The flame height changes from Test-2, Test-5, and Test-8 (where (**a**) is a coal pile of 40 cm diameter and 4 cm thickness, (**b**) is a coal pile of 60 cm diameter and 4 cm thickness, (**c**) is a coal pile of 80 cm diameter and 4 cm thickness).

The constant flame heights are 40 cm, 51 cm, and 56 cm for diameters ranging from 40 cm to 80 cm in Figure 6. This phenomenon occurs because flame heat feedback allows more coal to create flammable steam, leading to a taller flame. When evaluating flame heights at varying coal pile thicknesses (from 2 cm to 6 cm), however, flame heights remained unchanged at 51 cm. This discrepancy is due to the restricted heat transmission from radiation feedback, which prevents the increasing thickness of coal heaps from affecting the flame height. On the basis of the above study, it is possible to determine the maximum flame height by fitting experimental data onto flame heights and coal pile diameters. The fitting formula and fitting curve are shown in Equation (2) and Figure 8, and the maximum flame height is 56.33 cm, which may be used as a reference for future coal bunker designs.

$$y = -0.0075x^2 + 1.3x \tag{2}$$

where y is the flame height (cm) and x is the coal pile diameter (cm).

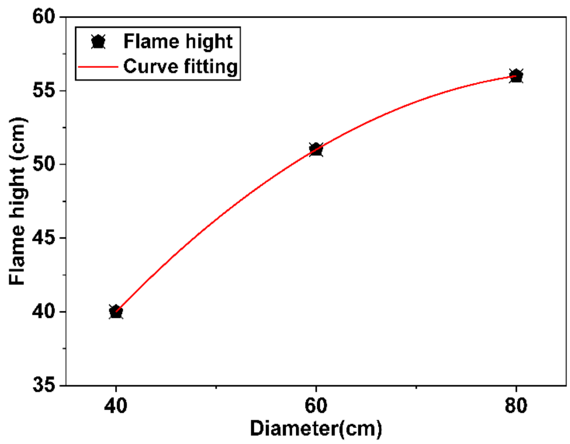
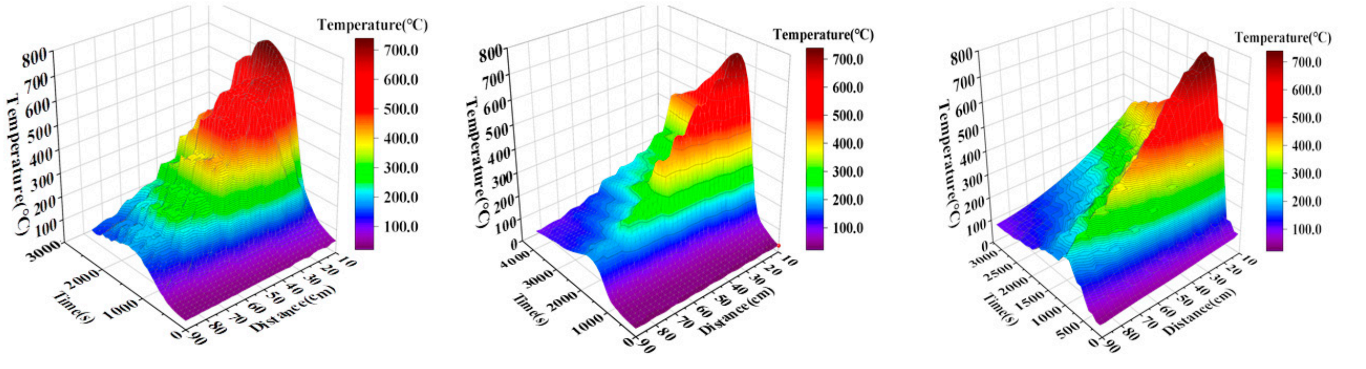


Figure 8. The flame height fitting curve with different diameters.

3.4. Flame Temperature

Previous burning rate analyses have shown that the diameter of the coal pile influences flame height. The greater the height of the flame, the larger its high-temperature region. In order to examine the longitudinal flame temperature distribution of coal piles, piles with thicknesses of 6 cm and dimensions of 40, 60, and 80 cm (Test-3, Test-6, and Test-9) are chosen. A group of vertically arranged thermocouples separated by 10 cm are positioned in the center of the coal pile to measure the longitudinal temperature distribution of the flame, as shown in Figure 9. When the combustible solid reaches the smoldering stage, the combustible solid becomes coke and continues to burn. At this time, the heat released by combustion will not dissipate rapidly, and there will be a localized area of high temperature near the coke, resulting in long-lasting harm to coal bunker components. Therefore, infrared thermography was used to estimate the coal pile surface temperature after combustion had entered the smoldering stage. The results are shown in Figure 10.



(a) Test-3 **(b)**Test-6 **(c)**Test-9

Figure 9. The flame temperature changes of Test-3, Test-6, and Test-9 (where (**a**) is a coal pile of 40 cm diameter and 6 cm thickness, (**b**) is a coal pile of 60 cm diameter and 6 cm thickness, (**c**) is a coal pile of 80 cm diameter and 6 cm thickness).

As can be seen in Figure 9, the flame temperature reaches its peak at a distance of 10 cm from the floor of the coal pile during the coal pile combustion process, but the temperature decreases progressively as the distance from the coal pile's floor increases. Meanwhile, it is discovered that the maximum flame temperature of 750 °C has not been significantly raised. The reason for this phenomenon is that the pyrolysis rate interferes with the combustion rate, thus affecting the heat feedback. In addition, it has been determined that the temperature of the smoke may approach 200 °C. However, according to current engineering practices in China, the steel structure's strength begins to increase as the temperature rises, decreases when the temperature exceeds 200 °C, and collapses at 537 °C. Consequently, it is critical to consider high-temperature fires and smoke for coal bunker safety in future designs. As can be seen from Figure 10, larger diameter coal piles are more likely to have greater high temperature zones, and the temperature at the center of a coal pile during the smoldering phase can reach approximately 939 °C, which is significantly higher than the flame temperature at other stages. Therefore, in future management of coal bunkers, the coal pile should avoid contact with the load-bearing structure within the coal bunker in order to prevent the coal bunker from collapsing.

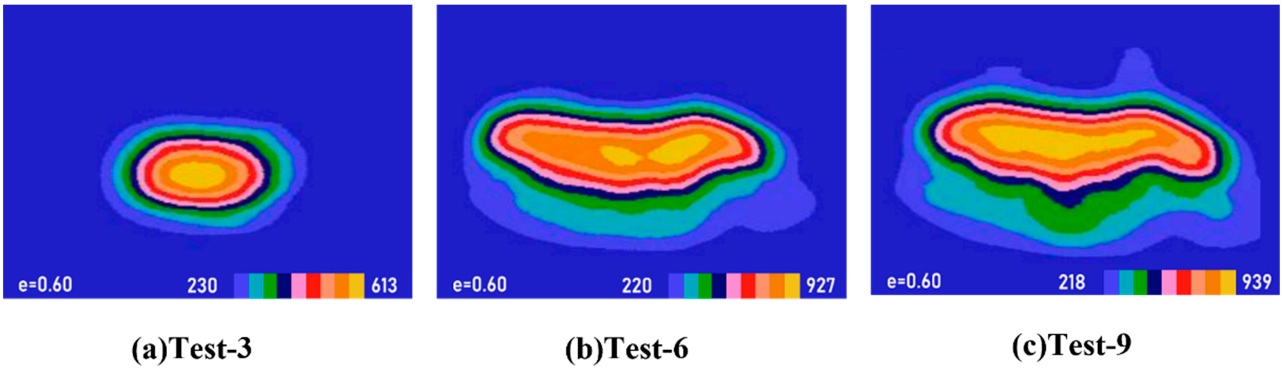


Figure 10. The surface temperature changes of Test-3, Test-6, and Test-9 in the smoldering stage (where (**a**) is a coal pile of 40 cm diameter and 6 cm thickness, (**b**) is a coal pile of 60 cm diameter and 6 cm thickness, (**c**) is a coal pile of 80 cm diameter and 6 cm thickness).

3.5. Radiant Heat Flux

Radiant heat flux is the radiant energy received per unit area in unit time. When a coal pile fire is formed, the heat and energy induced by the luminous flame and hot smoke will be released to the surrounding environment through the convective and radiative heat transfer processes. The possible ignition of adjacent coal piles might induce multiple coal pile fires to burn, and the resulting higher burning intensity, flame height, and outward radiation pose a great threat to the safety of surrounding people and devices, which is what causes structures to lose efficacy at the flame phase. Radiant heat flux can be measured using a water-cooled heat flow meter located 2.4 m from the coal reactor center. The results are shown in Figures 11 and 12.

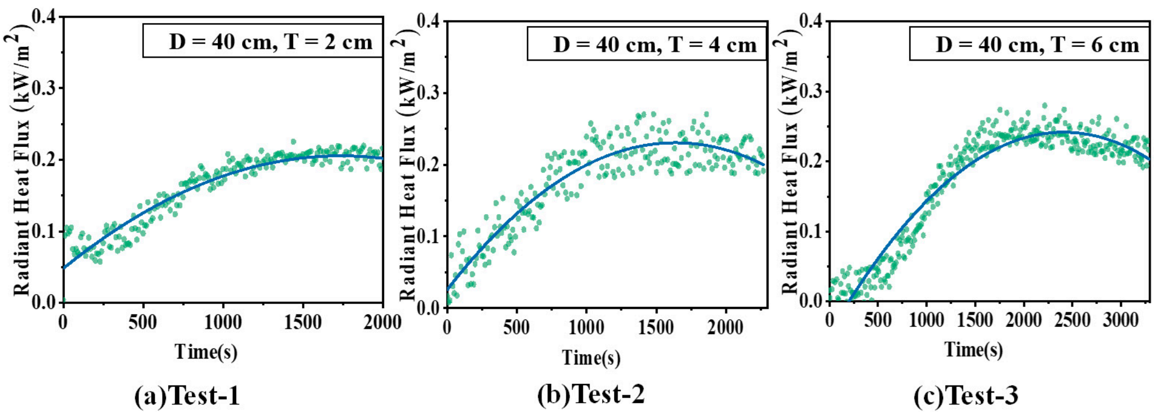


Figure 11. The radiant heat flux changes from Test-1 to Test-3 (where (**a**) is a coal pile of 40 cm diameter and 2 cm thickness, (**b**) is a coal pile of 40 cm diameter and 4 cm thickness, (**c**) is a coal pile of 40 cm diameter and 6 cm thickness).

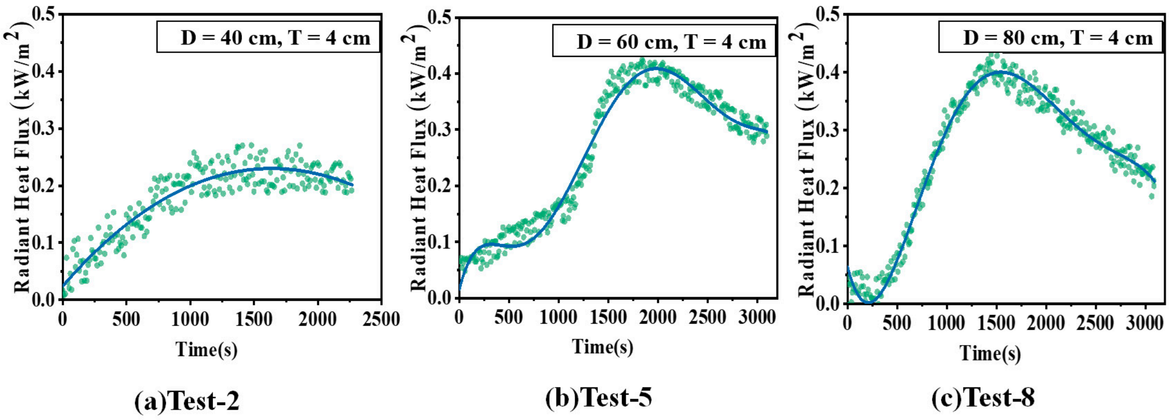


Figure 12. The radiant heat flux changes of Test-2, Test-5, and Test-8 (where (**a**) is a coal pile of 40 cm diameter and 4 cm thickness, (**b**) is a coal pile of 60 cm diameter and 4 cm thickness, (**c**) is a coal pile of 80 cm diameter and 4 cm thickness).

According to Figures 10 and 11, the maximum heat radiation flux at the stable stage was 0.25 KW/m^2, and the heat radiation flux changes depend on the diameter, not the thickness. Figure 13 shows the relationship between the coal pile's diameter and its heat radiation flux using the linear fitting method. When the thermal radiation flux safety criterion for destroying the coal bunker is 25 KW/m^2 and the thermal radiation damage guidelines from relevant articles are considered, the following equation (Equation (3)) can be used. If the distance between the coal pile and the coal bunker is 2.4 m, the maximum diameter is 587 cm.

$$Y = -0.001x^2 + 0.0187x - 0.32 \tag{3}$$

where Y is the radiant heat flux (KW/m^2) and x is the coal pile diameter (cm).

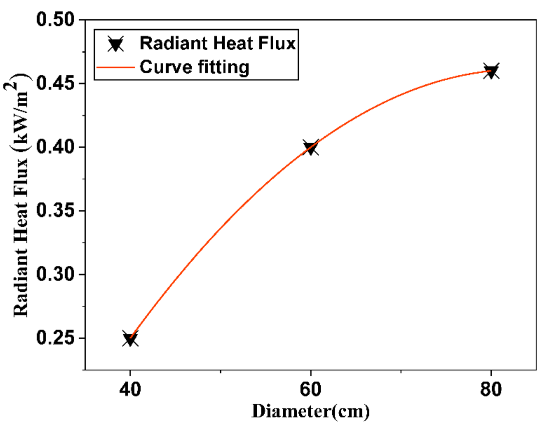


Figure 13. The radiant heat flux fitting curve with different diameters.

4. Conclusions

Coal bunkers are vital to the stability of power companies. As a result of the current situation of frequent coal bunker fire accidents and the absence of fire protection codes for coal bunkers, this research adopted a self-built coal pile combustion experimental platform to search for the key parameters affecting the coal bunker's security in order to provide a reference for coal bunker safety design. The following conclusions can be drawn:

(1) Burning experiments were done on nine different kinds of coal piles to get burning rate curves with different diameters and thicknesses. It is found from the experimental results that the diameter of the coal pile has no influence on the burning rate, presumably as a result of the interaction of the pyrolysis rate with the burning rate. Nevertheless, the thickness of the coal pile does have an effect on the steady

burning rate since it provides more fuel in the vertical direction. In addition, the maximum burning rate (10.5 ($g \cdot m^{-2} \cdot s^{-1}$)) of coal piles in the steady burning stage was determined based on the relationship between the burning rate and the thickness. The value can provide guidance and support for coal pile designs.

(2) Based on the flame height analysis of the results from the experiments, it could be seen from the results that increasing the diameter of coal piles can increase flame height, and this is attributed to increased fuel-air contact areas. For this reason, it is possible to estimate the maximum flame height at 56.33 cm, which can provide an important design guide for coal bunker height designs. In addition, taking measures to improve fire resistance, such as painting the roof of the coal bunker with fire-resistant paint, is essential to preventing collapse due to direct flame contact.

(3) As a result of the flame temperature analysis, it was determined that the maximum flame temperature of coal piles was independent of the coal pile size, and it was found from the experimental results that the flame temperature can reach above 800 °C and the smoke temperature can reach above 200 °C, which may damage the surrounding materials. Consequently, it is critical to consider high-temperature fire and smoke for coal bunker safety. In addition, we observe that the temperature of smoldering coal can reach temperatures of 900 °C in the smoldering stage. Therefore, in the future management of coal bunkers, the coal pile should avoid contact with the load-bearing structure within the coal bunker in order to prevent the coal bunker from collapsing.

(4) The research on radiant heat flux showed that the maximum heat radiation flux at the stable stage was 0.25 kW/m^2, and the heat radiation flux changes depend on the diameter, not the thickness. Based on the thermal radiation damage guideline and the fitting formula of fuel diameter and heat radiation flux, it can be calculated that the diameter of the coal pile should not exceed 587 cm when there is 2.4 m distance between the coal bunker and coal pile. For this reason, it is important that the design of the coal bunker take into consideration both the coal pile's fire separation distance from the coal bunker and avoid large coal piles.

Author Contributions: Conceptualization, L.Z. and P.F.; methodology, J.Z., P.F. and N.X.; validation, P.F.; formal analysis, L.Z.; investigation, L.Z. and P.F.; resources, L.Z. and P.F.; data curation, P.F., Z.W. and N.X.; writing—original draft preparation, L.Z. and P.F.; writing—review and editing, L.Z., Z.W. and J.Z.; visualization, P.F., Z.W. and N.X.; supervision, L.Z. and J.Z.; project administration, L.Z.; funding acquisition, L.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the National Key Research and Development Plan under Grant No. 2020YFC1522805 and the Key Research and Development Program of National Fire and Rescue Administration (No. 2022XFZD04).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The authors declare that the data supporting the findings of this study are available within the article.

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

1. Reza Khatami, Y.A.L. An overview of coal rank influence on ignition and combustion phenomena at the particle level. *Combust. Flame* **2016**, *164*, 22–34. [CrossRef]
2. Tan, B.; Li, X.; Zhang, X.; Zhang, Z.; Zhang, H. Research on initial prevention of spontaneous combustion in coal bunkers based on fire-extinguishing and fireproof inerting. *ACS Omega* **2022**, *7*, 3359–3368. [CrossRef] [PubMed]
3. Fisher, L. Destruction of the Maine (1898). Encyclopedia Britannica. 2023. Available online: https://www.britannica.com/event/destruction-of-the-Maine (accessed on 14 March 2023).
4. Singh, A.K.; Singh, R.; Singh, M.P.; Chandra, H.; Shukla, N. Mine fire gas indices and their application to Indian underground coal mine fires. *Int. J. Coal Geol.* **2007**, *69*, 192–204. [CrossRef]

5. Stracher, G.B.; Taylor, T.P. Coal fires burning out of control around the world: Thermodynamic recipe for environmental catastrophe. *Int. J. Coal Geol.* **2004**, *59*, 7–17. [CrossRef]
6. Zhang, Y.T.; Li, Y.Q.; Shi, X.Q.; Zhang, Y.J. Heat effects and kinetics of coal spontaneous combustion at various oxygen contents. *Energy* **2021**, *234*, 121299.
7. Varol, M.; Atimtay, A.; Bay, B.; Olgun, H. Investigation of co-combustion characteristics of low quality lignite coals and biomass with thermogravimetric analysis. *Thermochim. Acta* **2010**, *510*, 195–201. [CrossRef]
8. Onifade, M.; Genc, B. A review of research on spontaneous combustion of coal. *Int. J. Min. Sci. Technol.* **2020**, *30*, 303–311. [CrossRef]
9. Guo, Y.; Guo, F.; Zhou, L.; Guo, Z.; Miao, Z.; Liu, H.; Zhang, X.; Wu, J.; Zhang, Y. Investigation on co-combustion of coal gasification fine slag residual carbon and sawdust char blends: Physiochemical properties, combustion characteristic and kinetic behavior. *Fuel* **2021**, *292*, 120387. [CrossRef]
10. Kanca, A. Investigation on pyrolysis and combustion characteristics of low quality lignite, cotton waste, and their blends by TGA-FTIR. *Fuel* **2020**, *263*, 116517. [CrossRef]
11. Kaymakci, E.; Didari, V. Relations between coal properties and spontaneous combustion parameters. *Turk. J. Eng. Environ. Sci.* **2002**, *26*, 59–64.
12. Brooks, K.; Glasser, D. A simplified model of spontaneous combustion in coal stockpiles. *Fuel* **1986**, *65*, 1035–1041. [CrossRef]
13. Lu, X.; Deng, J.; Xiao, Y.; Zhai, X.; Wang, C.; Yi, X. Recent progress and perspective on thermal-kinetic, heat and mass transportation of coal spontaneous combustion hazard. *Fuel* **2022**, *308*, 121234. [CrossRef]
14. Xiao, Y.; Li, Q.W.; Deng, J.; Shu, C.M.; Wang, W. Experimental study on the corresponding relationship between the index gases and critical temperature for coal spontaneous combustion. *J. Therm. Anal. Calorim.* **2016**, *127*, 1009–1017. [CrossRef]
15. Jia, X.; Wu, J.; Lian, C.; Wang, J.; Rao, J.; Feng, R.; Chen, Y. Investigating the effect of coal particle size on spontaneous combustion and oxidation characteristics of coal. *Environ. Sci. Pollut. Res.* **2022**, *29*, 16113–16122. [CrossRef] [PubMed]
16. Cai, J.; Yang, S.; Hu, X.; Song, W.; Song, Y. Forecast of coal spontaneous combustion based on the variations of functional groups and microcrystalline structure during low-temperature oxidation. *Fuel* **2019**, *253*, 339–348. [CrossRef]
17. Ören, Ö.; Şensöğüt, C.; Şahbaz, O. Empirical modelling of oxidation behaviours of coals stored under different conditions. *Int. J. Min. Reclam. Environ.* **2019**, *34*, 159–178. [CrossRef]
18. Stracher, G.B. Chapter 10—Determination of the Characteristics of Coal-Spontaneous Combustion and the Danger Zone. In *Coal and Peat Fires: A Global Perspective*; Elsevier: Amsterdam, The Netherlands, 2019; pp. 173–193. [CrossRef]
19. Taraba, B. Aerial and subaquatic oxidation of coal by molecular oxygen. *Fuel* **2019**, *236*, 214–220. [CrossRef]
20. Guo, H.Z.; Gao, J.L.; Huang, B.Y. Apply of coal-bunker fire warning system based on ZigBee. In Proceedings of the IEEE Workshop on Electronics, Computer and Applications, Ottawa, ON, Canada, 8–9 May 2014. [CrossRef]
21. Guo, J.; Wen, H.; Zheng, X.; Liu, Y.; Cheng, X. A method for evaluating the spontaneous combustion of coal by monitoring various gases. *Process Saf. Environ. Prot.* **2019**, *126*, 223–231. [CrossRef]
22. Zhu, H.Q.; Song, Z.Y.; Tan, B.; Hao, Y.Z. Numerical investigation and theoretical prediction of self-ignition characteristics of coarse coal stockpiles. *J. Loss Prev. Process Ind.* **2013**, *26*, 236–244. [CrossRef]
23. Diaconu, B.M.; Cruceru, M.; Popescu, L.G. Mathematical modelling of the coal stockpile self-heating process. A case study. In Proceedings of the International Conference on Energy, Environment, Devices, Systems, Communications, Computers; EEDSCC '11, Venice, Italy, 8–10 March 2011.
24. Michalec, Z.; Michalcová, V.; Blejchař, T.; Bojko, M.; Kozubková, M. CFD simulations of the effect of wind on the spontaneous heating of coal stockpiles. *Fuel* **2014**, *118*, 107–112.
25. Kumaran, S.M.; Raghavan, V.; Rangwala, A.S. A Parametric Study of Spontaneous Ignition in Large Coal Stockpiles. *Fire Technol.* **2020**, *56*, 1013–1038. [CrossRef]
26. Akgun, F.; Essenhigh, R.H. Self-ignition characteristics of coal stockpiles: Theoretical prediction from a two-dimensional unsteady-state model. *Fuel* **2001**, *80*, 409–415. [CrossRef]
27. Yuan, L.; Smith, A.C. CFD modeling of spontaneous heating in a large-scale coal chamber. *J. Loss Prev. Process Ind.* **2009**, *22*, 426–433. [CrossRef]
28. Yang, J.; Sun, B. Spontaneous Combustion Factor Analysis and Control Techniques for Coal Bin. *Eng. Sci. Technol. I Ser.* **2014**, 386–388.
29. Zhang, H.; Sasaki, K.; Zhang, X.; Sugai, Y.; Wang, Y. Formation of Cross-linked Gel from Complex Water-Solution of Sodium Metasilicate Nonahydrate and Polyvinyl Alcohol to Inhibit Spontaneous Coal Combustion. *Combust. Sci. Technol.* **2022**, *194*, 2308–2324. [CrossRef]
30. Yuan, J.; Zhao, J.; Wang, W.; Yang, R.; Fu, M. The study of burning behaviors and quantitative risk assessment for 0# diesel oil pool fires. *J. Loss Prev. Process Ind.* **2021**, *72*, 104568.
31. Viegas, D.X.; Almeida, M.; Miranda, A.I.; Ribeiro, L.M. Linear model for spread rate and mass loss rate for mixed-size fuel beds. *Int. J. Wildland Fire* **2010**, *19*, 531–540. [CrossRef]
32. Lu, K.; Chen, X.; Luo, Z.; Wang, Y.; Su, Y.; Zhao, T.; Xiao, Y. The inhibiting effects of sodium carbonate on coal dust deflagration based on thermal methods. *Fuel* **2022**, *315*, 123122. [CrossRef]

33. Chen, J.; Zhang, B.; Song, Y. Flame recognition based on statistical RGB color model. *J. Jiangsu Univ. Sci. Technol.* **2017**, *31*, 178–184.
34. Celik, T.; Demirel, H.; Ozkaramanli, H.; Uyguroglu, M. Fire detection using statistical color model in video sequences. *J. Vis. Commun. Image Represent.* **2007**, *18*, 176–185. [CrossRef]