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Research Article

Study on Spontaneous Combustion Law and Prevention Technology of Abandoned Coal in Goaf of Coal Mine

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The spontaneous combustion of coal in goaf areas is a significant natural disaster encountered during coal mining operations. To investigate the oxygen consumption characteristics of different coal types, we conducted TG experiments and closed oxygen consumption experiments using seven coal samples exhibiting various degrees of metamorphism. The findings revealed the following key observations: During the oxidation combustion process of coal, the absorbed heat originates from the physical and chemical adsorption of coal and oxygen. The first exothermic peak on the DSC curve represents the maximum combustion temperature of volatile matter and signifies the initiation of coal burning. Coal with higher ignition temperatures is less prone to spontaneous combustion. Analyzing the thermogravimetric curves, we observed that the ignition temperatures of 15# coal and 8+9# coal predominantly extracted from Duanwang Coal Mine are higher compared to the ignition temperature of the 4# coal seam (known for its susceptibility to spontaneous combustion) in Jiudaoling Coal Mine, Liaoning. This observation aligns with their nonspontaneous combustion characteristics. In the closed oxygen consumption experiment, we determined the volume oxygen consumption attenuation coefficients for the main mining areas' 8+9# and 15# coal seams as 3.9001×10^{-4} and 3.83559×10^{-4}, respectively. Additionally, the critical oxygen consumption concentrations were measured as 15.71% and 16.78%. The shortest spontaneous combustion periods were determined to be 119.24 days and 121.25 days, respectively, for the aforementioned coal seams. To mitigate spontaneous combustion, the addition of inhibitors is necessary. The selection of an appropriate inhibitor depends on the increase in ignition activation energy. Notably, coal samples treated with a 15% $MgCl_2$ inhibitor exhibited the highest increase in ignition activation energy. Hence, we concluded that a 15% $MgCl_2$ inhibitor is the most suitable ratio for preventing spontaneous combustion.

1. Introduction

Coal, as a primary energy source in China, is susceptible to spontaneous combustion, posing a significant threat to coal mining operations [1–3]. Consequently, preventing and controlling the spontaneous combustion of residual coal has always been a crucial topic in coal production and research, with direct implications for safety and economic benefits [4–6].

Spontaneous combustion of coal is a natural disaster encountered in coal mine production and is a key aspect of fire prevention and extinguishing. Consequently, it has become a prominent research area for scholars worldwide [7–10]. Zhang et al. [11] investigated the microscopic and macroscopic characteristics of coal with varying degrees of metamorphism using functional groups as microscopic characteristic parameters and parameters such as gas generation rate, oxygen consumption rate, gas concentration, heat release rate, and characteristic temperature as macroscopic characteristic parameters. Wen et al. [12, 13] derived calculation formulas for the coal spontaneous combustion process and established a three-dimensional dynamic mathematical model of coal spontaneous combustion by conducting experiments on coal spontaneous combustion and examining the relationship between loose coal particle size and oxidation spontaneous combustion. Moreover, international

Table 1: The test coal sample selection and coal sample numbers.

No.	Coal seam	Coal mine	Remarks
No. 1	Layer 4#	Jiudaoling Coal Mine in Liaoning Province	Coal seams are prone to spontaneous combustion. They are used as reference coal samples for this study. Long flame coal (bituminous coal)
No. 2	Layer 8#-1	Changping Coal Mine of Shanxi Jinmei Group 84301 working face of Fushan well	Spontaneous coal seam (class II), the metamorphism belongs to lean coal—anthracite stage
No. 3	Layer 8#-2		
No. 5	Layer 15#	150405 working face in Duanwang Coal Mine in Shanxi Province	Spontaneous coal seam (class II). Lean coal (bituminous coal)
No. 6	Layer 8+9#	090506 working face in Duanwang Coal Mine in Shanxi Province	Spontaneous coal seam (class II). Between spontaneous combustion and nonspontaneous combustion. Lean coal (bituminous coal)
No. 8	Layer 11#	Duanwang Coal Mine in Shanxi Province	Unworkable seam, drill hole sampling
No. 9	Layer 13#		
No. 89	Layer11# and 13#	Duanwang Coal Mine in Shanxi Province	Unworkable seam, drill hole sampling

researchers have utilized the Arrhenius formula and heat and mass transfer theory to develop mathematical models that simulate and study coal spontaneous combustion processes and predict the duration of spontaneous combustion [14–17]. Regarding spontaneous combustion in goaf areas, fire prevention and control technologies primarily encompass chemical inhibitors, plugging, water injection, grouting, pressure equalization, three-phase foam, inert gas, aerosol, and other fire prevention and extinguishing measures [18, 19].

However, relying on a single fire prevention measure is often insufficient in effectively combating spontaneous combustion. Therefore, comprehensive approaches integrating various fire prevention and control techniques are necessary for mitigating the risks associated with spontaneous combustion.

2. Experimental Method

2.1. Coal Sample Selection. The coal samples used in the test were taken from Liaoning Jiudaoling Coal Mine, Shanxi Jinmei Group Changping Coal Mine, and Shanxi Duanwang Coal Mine. After underground operation, seven raw coal samples and one mixed coal sample were collected from different coal seams and working faces. The experimental study also selected typical coal samples from different mines; that is, the coal samples in other mines are used as the reference and comparative analysis objects of the study. The test coal sample selection and coal sample numbers are shown in Table 1.

Layer 8+9# and layer 15# are the main coal seams of Duanwang Coal Mine. Although layer 11# and layer 13# are unminable coal seams, after mining layer 15#, they loosen and connect to the goaf, which constitutes the possibility of spontaneous combustion and oxidation of the coal left over from the goaf. Therefore, the coal samples of layer 15#, layer 8+9#, layer 11#, and layer 13# are taken as the main samples of this study. And the coal sample of layer 4# of Jiudaoling Coal Mine in Liaoning Province is taken as the reference coal sample. Coal samples collected in the mine are sealed immediately to avoid oxidation. The test coal sample grinding was less than 250 mesh; then after being vacuum-dried for 24 hours, they were stored in a drying dish.

Figure 1: Thermogravimetric analyzer instrument.

2.2. TG Experiments. Coal samples in the experiments are collected from the underground of Duanwang Mine and Jiudaoling Coal Mine (reference mine) in Liaoning Province. Coal samples are the original coal samples and mixed coal samples of different coal seams and different working faces. The coal samples are ground to less than 250 mesh in the laboratory and stored in a dry container.

The experimental instrument is the German made STA449C comprehensive thermogravimetric analyzer as shown in Figure 1. The experimental conditions are as follows: the temperature rises 5°C per minute, the flow rate of oxygen of the reaction gas is 15 ml/min, the flow rate of nitrogen is 45 ml/min, the sample mass is 20-25 mg, and the reaction temperature range is 22°C~590°C; thus, the TG analysis curve can be obtained.

2.3. Closed Oxygen Consumption Test. The closed oxygen consumption experiment consists of one closed coal sample tank, gas path equipment, and automatic gas concentration testing equipment, as shown in Figure 2. The RS450 data collector is used for data collection and automatic recording. The concentration of oxygen and carbon monoxide gas is automatically recorded every 30 s. 5643 data are collected in the experiment, which is carried out at 25°C.

3. Results and Discussion

3.1. Thermogravimetric Analysis. According to the thermogravimetric analysis curve of experimental coal samples

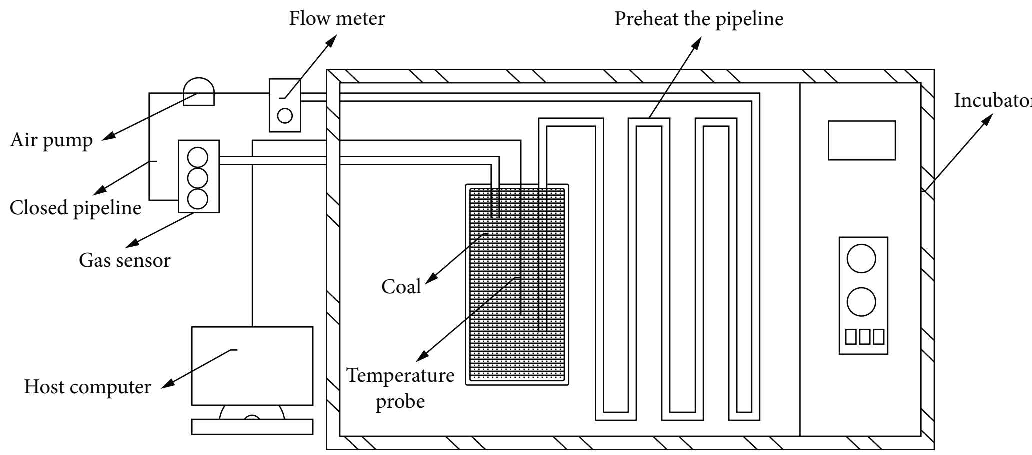

Figure 2: The experiment instrument of the closed oxygen consumption.

under the increasing temperature condition, the process of coal oxidation spontaneous combustion can be divided into three stages: water loss stage, oxidation weight gain stage, and combustion weight loss stage, as shown in Figure 3.

Thermal gravimetric (TG) curve of a coal sample of layer 4# (no. 1) in Jiudaoling Coal Mine in Liaoning Province for reference as shown in Figure 3.

Coal sample no. 1 is mapped from 117.0 to 271.4°C for oxidation spontaneous combustion dehydrating activation energy as shown in Figure 4.

The fitting equation of kinetic parameters at the combustion stage of oxidation spontaneous combustion of coal sample no. 1 is as follows: $Y = 16.77881 - 14751.42206X$; relevancy: 0.94725; and activation energy: $E = 122.62$ kJ/mol. The ignition activation energy of eight different coal samples was calculated by using the ignition activation energy method. According to thermogravimetric analysis of coal samples, the ignition temperature range and ignition activation energy of each coal sample are shown in Table 2.

The ignition temperature and water loss temperature of the experimental coal samples are presented in Table 3. A higher ignition temperature indicates a reduced likelihood of spontaneous combustion in coal. In Duanwang Coal Mine, Shanxi Province, the ignition temperature of layer 15# and layer 8+9# is significantly higher compared to layer 4# in Jiudaoling Coal Mine, suggesting that layer 15# and layer 8+9# exhibit different characteristics in terms of their susceptibility to spontaneous ignition. When comparing the coal seams in Duanwang Coal Mine, the ignition temperatures of layer 15#, layer 8+9#, and the unminable layers 11# and 13# overlying layer 15# are closely aligned. These temperatures are notably higher than that of layer 4# in Jiudaoling, Liaoning, which is prone to spontaneous combustion.

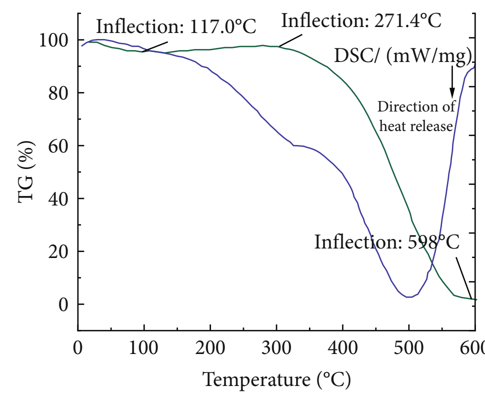

Figure 3: Thermal gravimetric (TG) curve of coal sample no. 1.

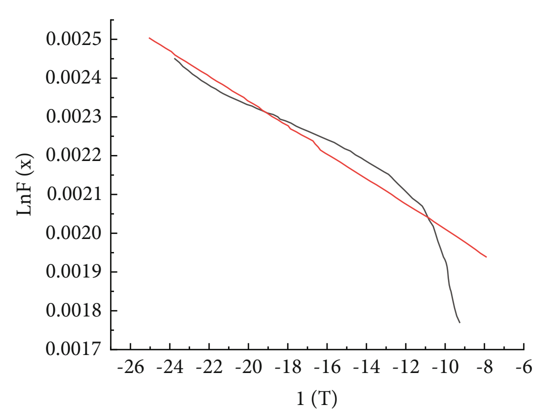

Figure 4: Relation between ln $F(x)$ and $1/T$ at the ignition stage of oxidation spontaneous combustion of coal sample no. 1.

3.2. Oxygen Consumption Experiment and Determination of Spontaneous Ignition Period of Coal Sample in Duanwang Mine

3.2.1. Sealed Oxygen Consumption Experiment of Layer 15# (Coal Samples of 150405 Working Face). In the closed oxygen consumption state, the oxygen concentration decreases continuously and eventually reaches a stable value c_b. The oxygen concentration in the sealed tank approximately follows the negative exponential function distribution.

$$c(\tau) = c_b + (c_0 - c_b) \cdot e^{-\lambda_c \cdot \tau}. \quad (1)$$

Table 2: Experimental data of thermogravimetric analysis of coal samples at oxidation and combustion stage.

Coal sample number	Ignition temperature range (°C)	Ignition activation energy (kJ/mol)	Relevancy
No. 1 (reference)	117.0~271.4	122.62	0.94725
No. 2 (reference)	162.9~375.4	118.57	0.99586
No. 3 (reference)	146.5~354.1	117.19	0.980740
Layer 15# (no. 5)	154.6~350.0	140.57	0.99517
Layer 8 + 9 # (no. 6)	155.5~336.9	134.86	0.99241
Layer 11# (no. 8)	151.0~326.1	141.8	0.99349
Layer 13# (no. 9)	145.0~328.5	132.34	0.99424
No. 89	179.6~340.7	167.15	0.98739

Table 3: Water loss temperature and ignition temperature of experimental coal sample (temperature at the end of weight gain).

Coal sample test number	Sampling location and source	End point temperature of water loss (°C)	Ignition temperature (°C)
No. 1 (reference)	Jiudaoling Coal Mine in Liaoning Province, layer 4#	117.0	271.4
No. 2 (reference)	Layer 8#-1 in Changping Mine, Jinmei in Shanxi Province	162.9	375.4
No. 3 (reference)	Layer 8-2 in Changping Mine, Jinmei in Shanxi Province	146.5	354.1
No. 5 (layer 15#)	Layer no.15 of Duanwang Mine in Shanxi Province, 150405 working face	154.6	350.0
No. 5 (layer 8+9#)	Layer 8+9# coal in Duanwang Mine in Shanxi Province, 090506working face	155.5	336.9
No. 8 (layer 11#)	Layer 11# Duanwang Mine in Shanxi Province. Borehole sampling through layer	151.0	326.1
No. 9 (layer 13#)	Layer 13# Duanwang Mine in Shanxi Province. Borehole sampling through layer	145.0	328.5
No. 89 (layer 11# and 13# mix)	Layer 11+13, Duanwang Mine in Shanxi. Borehole sampling through layer	179.6	340.7

In formula (1), $c(\tau)$ is the oxygen concentration over time in a closed tank (mol/l), c_0 is the initial concentration of oxygen (mol/l), λ_c is the oxygen concentration decay rate (s^{-1}), τ is the oxidation time (s), and c_b is the minimum oxygen concentration of coal oxidized in a closed environment (mol/l).

Supposing $\gamma = (dc(\tau))/d\tau$, γ is the volume oxygen consumption rate, which comes to

$$\gamma = -\lambda_c \cdot (c_0 - c_b) e^{-\lambda_c \cdot \tau}. \quad (2)$$

Figure 5 shows the O_2 concentration change curve of coal samples of layer no. 15 in the closed tank. Figure 6 shows the variation curve of the CO concentration of coal samples from layer no. 15 in the closed tank. It can be seen from the experimental result that with the change of time because of the oxygen consumption, the oxygen concentration in the tank becomes lower and lower, and the coal sample no longer oxidizes after it reaches stability. Due to the oxidation reaction of coal samples, oxygen is constantly consumed, so the concentration of CO gas in the tank increases continuously from zero. On the whole, oxygen concentration in the experimental tank gradually decreased and CO gradually increased. In addition, the experimental results can also show that the coal sample of layer 15# can release CO at room temperature (low temperature), but it is much smaller than the coal that is easy to naturally ignite. It is not the same as people's common sense for the production of CO conditions.

3.2.2. Parameter and Regression Analysis of Closed Oxygen Consumption Experiment of Layer No. 15 (Coal Sample No. 5). Based on the experimental findings, it was observed that the oxygen consumption rate of the coal sample from the 150405 working face of layer 15# exhibited a relatively slower trend. The data collected from the records displayed a sawtooth shape on the distribution curve. In order to ensure data accuracy, a filtering and organizing process was implemented, excluding data points that did not focus on significant changes. A total of 5643 samples were utilized for the regression analysis of closed oxygen consumption test results for each coal sample in Duanwang Mine.

(1) Regression calculation of CO concentration. The results of linear regression are shown in Figure 7. The regression gives us a linear equation $Y = 228.13837 - 214.30982 \times 10 - 5.07017E - 4 \cdot X$. The regression coefficient can be obtained by comparing it with Equation (2), $\lambda_c = 5.07017 \times 10 - 4$, and $c_b =$

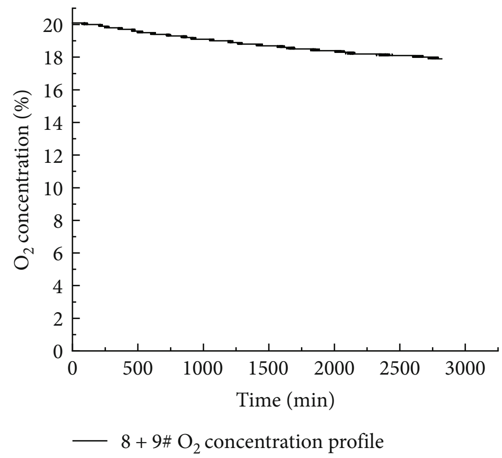

Figure 5: The change curve of O_2 concentration observed in the closed oxygen consumption experiment of coal sample of layer no. 15.

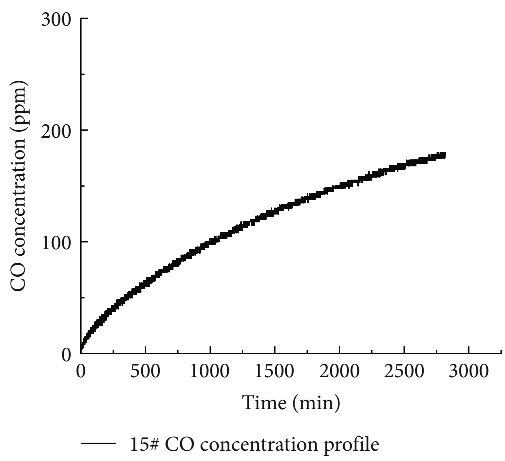

Figure 6: Variation curve of CO concentration observed by closed oxygen consumption experiment of coal sample of layer no. 15.

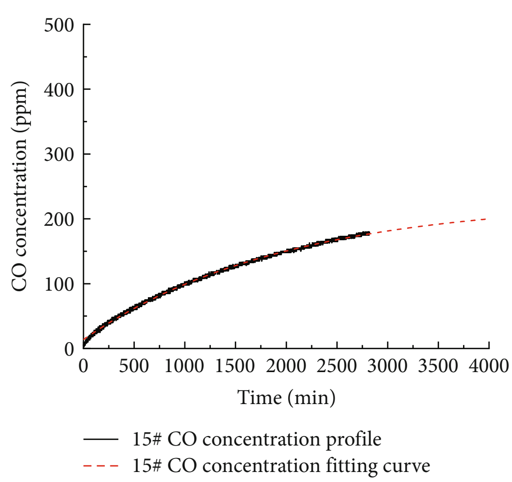

Figure 7: Regression curve of CO concentration change in closed oxygen consumption experiment of layer 15# coal sample.

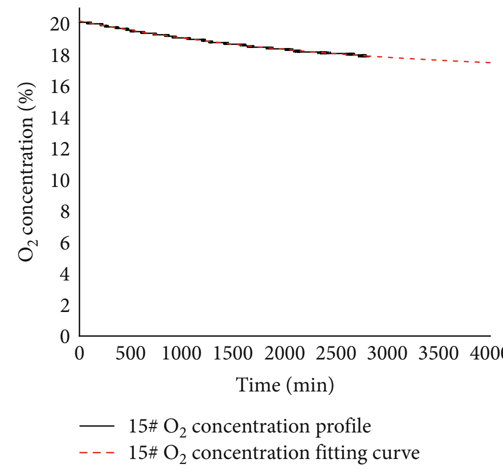

Figure 8: Regression curve of O_2 concentration change in closed oxygen consumption experiment of layer 15# coal sample.

228.13837. λ_c is the CO concentration growth coefficient, and c_b is the upper limit of CO concentration

(2) O_2 consumption velocity regression calculation. The results of linear regression are shown in Figure 8, and it gives us a linear equation: $Y = 16.78088 + 3.40001 \times 10 - 3.83559E - 4 \cdot X$. The regression coefficient can be obtained: $\lambda_c = 3.83559 \times 10 - 4$ and $c_b = 16.78088$. λ_c is the attenuation coefficient of O_2 concentration, and c_b is the lower limit of O_2 concentration. The experimental results are shown in Figure 8. The oxygen consumption attenuation coefficient (volume oxygen consumption velocity constant) in the coal sample tank is 3.83559×10^{-4}, and the lowest oxygen consumption concentration is 17.81%. The lower limit of oxygen consumption concentration of coal sample is 16.78% (it can be used as an inert indicator)

The experiment shows that when layer 15# (coal sample of 150405 working face) is below the lower limit of the oxygen concentration of 16.78%, the coal no longer consumes oxygen, and the spontaneous combustion oxidation of coal is very weak, almost inert.

3.2.3. Determination of Spontaneous Ignition Period of Layer No. 15. According to the previous experiment, the oxygen consumption attenuation rate in the coal sample tank of Jiudaoling Coal Mine is 2.7356×10^{-3}, which is 6.9256 times that of the coal sample test result of Duanwang Mine. In the experiment of natural temperature rise, the shortest spontaneous ignition period of Jiudaoling Coal Mine is 17 days. At the same time, according to the consistent relationship between the shortest spontaneous ignition period and the oxygen consumption rate, the shortest spontaneous ignition period of layer no. 15 in the main mining of Duanwang Group can be inferred as $17\,\text{days} \times 2.7356/0.383559 = 121.25$ days.

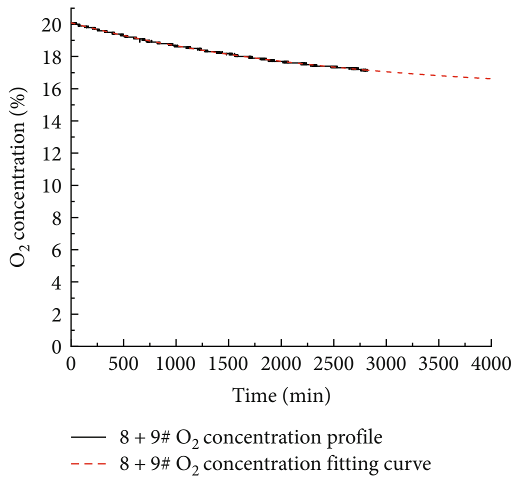

Figure 9: Regression curve of O_2 concentration observed in closed oxygen consumption experiment of layer 8+9# coal sample.

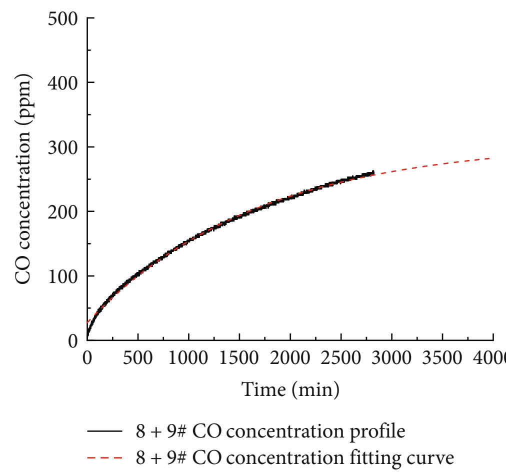

Figure 10: Regression curve of CO concentration observed by closed oxygen consumption experiment of layer 8+9# coal sample.

It can be seen that the natural ignition period of layer no. 15 in Duanwang Mine is relatively long. The shortest spontaneous ignition period was 121.25 days.

Considering the oxidation inertness of layer 15# shown in the previous experimental research, it is also fully manifested in the shortest spontaneous ignition period, which reflects a good consistency.

3.2.4. Experimental Result of Closed Oxygen Consumption of Layer 8+9# (Coal Sample No. 6)

(1) Figure 9 shows the calculation result of the linear regression of O_2 consumption velocity. The linear equation obtained by regression is as follows: The offset under the asymptote of minimum oxygen concentration (regression-adjusted empirical value) is 15.71%. The calculation results of linear regression are shown in Figure 9, and the linear equation is obtained by the following regression: $Y = 15.71483 + 4.37966 \times 10 - 3.9001E - 4 \cdot X$

The regression coefficient can be obtained by comparing it with Equation (2) $\lambda_c = 3.9001 \times 10 - 4$ and $c_b = 15.71483$, λ_c is the attenuation coefficient of O_2 concentration, and c_b and is the lower limit of O_2 concentration.

Analysis of coal sample experimental results in Duanwang Mine is that the oxygen consumption attenuation coefficient in the coal sample tank is 3.9001×10^{-4}, and the lowest oxygen consumption concentration is 17.23%. The lower limit of oxygen concentration of coal sample consumption is 15.71%.

(2) Regression calculation of CO concentration. The results of linear regression are shown in Figure 10, and linear equation is obtained by regression $Y = 308.26857 - 280.72355e - 5.98174E - 4 \cdot X$; the regression coefficient can be obtained: $\lambda_c = 5.98174 \times 10 - 4$ and $c_b = 308.26857$. λ_c is the CO concentration growth coefficient, and c_b is the upper limit of CO concentration

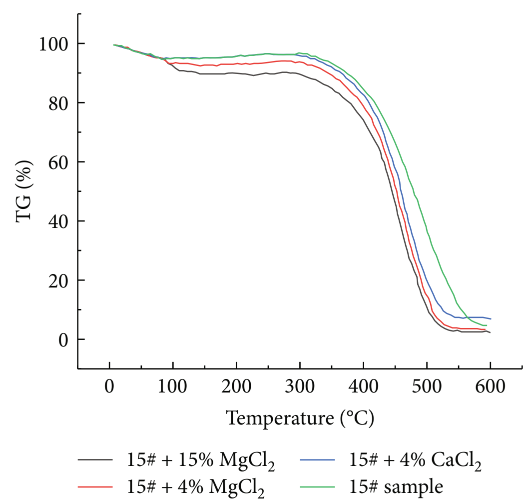

Figure 11: No. 1 TG curve of coal sample with inhibitor added.

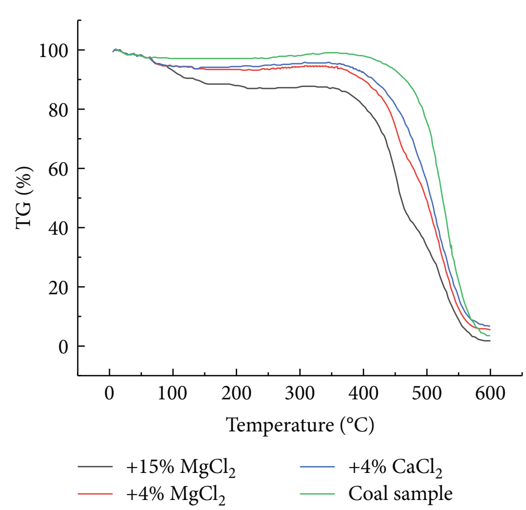

Figure 12: No. 2 TG curve after addition of blocking agent.

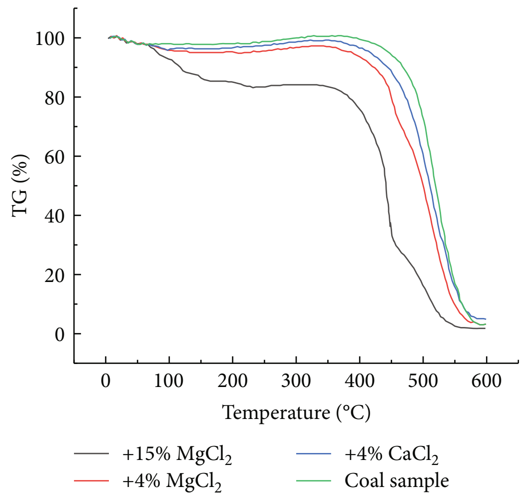

Figure 13: TG curve of sample no. 3 after adding inhibitor.

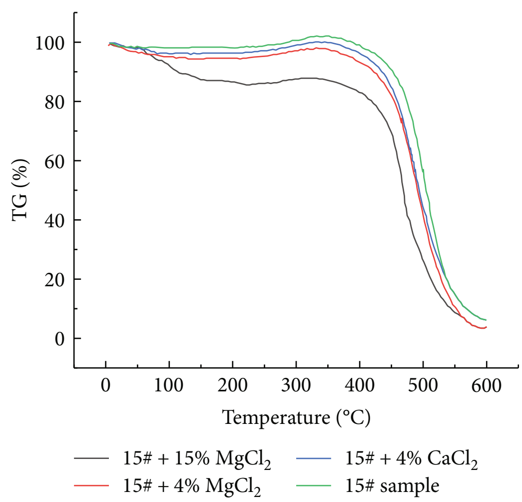

Figure 14: TG curve of coal sample in layer 15 after adding retarder.

The analysis of experimental results is as follows: The increase coefficient of CO oxide gas concentration in coal sample tank is 5.98174×10^{-4}. The upper limit of oxygen consumption CO concentration of coal sample is 308.26857 ppm.

3.2.5. Determination of the Shortest Spontaneous Ignition Period of Layer 8+9#. According to the oxygen consumption rate, the shortest spontaneous ignition period of layer 8+9# in Duanwang Mine is $17\,\text{days} \times 2.7356/0.39001 = 119.24$ days. It can be seen that the natural ignition period of layer 8+9# in Duanwang Mine is shorter. The shortest spontaneous ignition period is 119.24 days.

The oxygen consumption rate of layer 8+9# is faster than that of layer 15#, and the shortest spontaneous ignition period is shorter, which is consistent with the conclusion of infrared analysis. The provided reference for the above research conclusions cannot be used as the only indicator in practice (reference indicator).

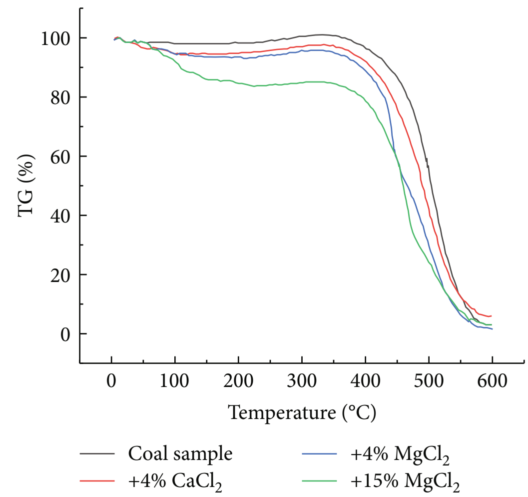

Figure 15: TG curve of sample no. 6 after adding inhibitor.

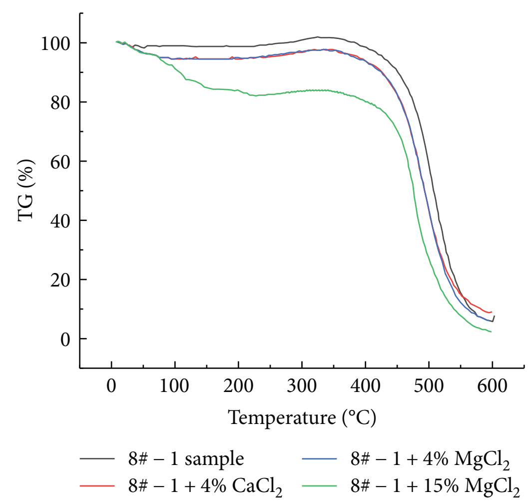

Figure 16: TG curve of sample no. 8 after adding inhibitor.

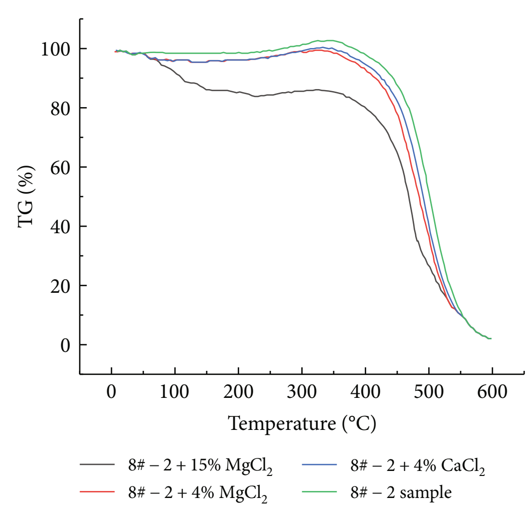

Figure 17: No. 9 TG curve after addition of blocking agent.

Table 4: Comparison of ignition activation energy between coal samples without inhibitor and with 4% $CaCl_2$ inhibitor.

Coal sample	No blocking agent coal E_1	R_1	After adding inhibitor coal E_2	R_2	Change in activation energy $E_0 = E_2 - E_1$
No. 1 (reference)	122.62	0.947295	137.07	0.957907	14.85
No. 2 (reference)	118.57	0.995854	127.04	0.932112	8.47
No. 3 (reference)	117.19	0.980744	91.99	0.994968	-25.2
No. 5 (15# layer)	140.57	0.994579	128.76	0.990811	-11.81
No. 6	134.86	0.992412	133.20	0.935610	-1.66
No. 8	141.80	0.992549	138.46	0.988901	-3.34
No. 9	132.34	0.993876	128.14	0.988914	-4.2

Table 5: Comparison of ignition activation energy between coal samples without and with 4% $MgCl_2$ inhibitor.

Coal sample number	No blocking agent coal E_1	R_1	After adding inhibitor coal E_2	R_2	Change in activation energy $E_0 = E_2 - E_1$
No. 1 (reference)	122.62	0.947295	122.56	0.947112	-0.06
No. 2 (reference)	118.57	0.995854	169.34	0.947728	50.77
No. 3 (reference)	117.19	0.980744	155.03	0.949703	37.13
No. 5 (layer 15#)	140.57	0.994579	150.68	0.992349	10.11
No. 6	134.86	0.992412	168.12	0.970989	33.26
No. 8	141.80	0.992549	167.43	0.946054	25.63
No. 9	132.34	0.993876	128.63	0.994922	-3.71

Table 6: Comparison of ignition activation energy between coal samples without inhibitor and with 15% $MgCl_2$ inhibitor.

Coal sample	No blocking agent coal E_1	R_1	After adding inhibitor coal E_2	R_2	Change in activation energy $E_0 = E_2 - E_1$
No. 1 (reference)	122.62	0.947295	152.71	0.966805	30.09
No. 2 (reference)	118.57	0.995854	194.32	0.969737	75.75
No. 3 (reference)	117.19	0.980744	209.41	0.970496	92.22
No. 5 (15# layer)	140.57	0.994579	178.64	0.975889	38.07
No. 6	134.86	0.992412	188.52	0.961331	53.66
No. 8	141.80	0.992549	196.24	0.943866	54.44
No. 9	132.34	0.993876	184.04	0.974814	51.7

3.3. Research on Fire Prevention with Retarder Based on Thermogravimetric Analysis. Based on the study of the inhibition mechanism, $MgCl_2$ and $CaCl_2$ metal halogens are selected as the inhibitors. According to the previous research results, three matching solutions are prepared, which are 4% $MgCl_2$ solution, 15% $MgCl_2$ solution, and 4% $CaCl_2$ solution, respectively. Add 500 mg of coal sample into a beaker of 500 ml distilled water, then add 0.5 ml of the configured inhibitor, stir well, and put into 30°C constant temperature water for 120 hours. Filter the compound with filter paper, rinse it, put it in a vacuum drying oven for 24 hours, seal, and store it in a glass dryer for use.

The TG curves of the same coal sample without and with inhibitor are shown in Figures 11–17.

As can be seen from Figures 11–17, TG curves of the same coal sample have changed greatly without and with the addition of inhibitor, which greatly reduces the oxidation activity of coal and the possibility of spontaneous combustion oxidation of coal.

Based on the calculation method of ignition activation energy with difficulty in spontaneous combustion, the solution with the maximum increase of ignition activation energy is found as the inhibitor. The results are shown in Tables 4–6. After adding the inhibitor, the inhibitor is selected according to the increase of ignition activation energy. The ignition activation energy of coal samples with 15% $MgCl_2$ inhibitor is generally increased the most. Therefore, 15%$MgCl_2$ solution is selected as the best proportion of the inhibitor.

4. Conclusion

(1) Based on thermogravimetric analysis, we obtained the kinetic parameter fitting equation for the oxidation

spontaneous combustion stage of each coal sample, along with their respective ignition activation energies, by analyzing the thermogravimetric curves of coal samples during the oxidation combustion process at temperatures ranging from 25°C to 600°C. The higher the ignition activation energy, the less prone the coal is to spontaneous combustion. Experimental results indicate that the activation energy for coal sample no. 1 is 122 kJ/mol, while for layer 15# (no. 5), it is 140.8 kJ/mol, and for layer 8+9# (no. 6), it is 134.86 kJ/mol. Consequently, coal sample no. 1 exhibits a lower susceptibility to spontaneous combustion compared to layer 15# (no. 5) and layer 8+9# (no. 6)

(2) By conducting closed oxygen consumption experiments on layer 15# and layer 8+9#, we derived a regression curve depicting the changes in O_2 and CO concentrations. It is evident that the lower limit of oxygen consumption concentration for layer 15# coal samples is 16.78%, while for layer 8+9# coal samples, it is 15.71%. However, despite these lower oxygen consumption concentrations, coal in Liaoning Jiudaoling Coal Mine is prone to self-ignition, with a spontaneous ignition period of 17 days. Based on the above data, we can infer that the shortest spontaneous ignition period for layer 15# in Duanwang Coal Mine is 121.25 days, while for layer 8+9#, it is 119.24 days. Considering the experimental data on ignition activation energy and spontaneous ignition period for all the aforementioned coal samples, layer 15# in Duanwang Coal Mine demonstrates a lower susceptibility to spontaneous combustion compared to layer 8+9#

(3) This study also utilizes a calculation method for determining the ignition activation energy, which is crucial in addressing the challenges associated with coal spontaneous combustion. By finding a solution that increases the maximum ignition activation energy, it is possible to reduce the oxidation rate of coal at low temperature

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

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