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Research on Reaction Mechanism of Different Stages of Lean Coal Spontaneous Combustion Based on Thermogravimetric Analysis: A Case Study of 1307 Working Face

Wenshuai Zhao[1] Jiayi Zhou[2] Jianing Wang[1] Chao Gao[1]

1. School of Coal Engineering, Shanxi Datong University, Datong, Shanxi;
2. Oilfield Technology Engineering Company, CNOOC Energy Technology & Services Company Limited, Tianjin

Abstract: In response to the urgent need for preventing and controlling the spontaneous combustion of abandoned coal in goaf areas of high-gas mines, this paper focuses on the lean coal located in the 1307 working face of a specific mine as the research subject. Through a combination of on-site sampling, chromatographic oxygen inhalation identification, and thermogravimetric-differential scanning calorimetry experiments, this study systematically reveals the dynamic evolution of the spontaneous combustion process of lean coal. Research indicates that this coal seam exhibits a pronounced tendency for spontaneous combustion, and its oxidation process demonstrates significant phase characteristics. During the increase in temperature gradient, the coal sample undergoes a continuous transformation characterized by initial weight loss due to water evaporation, followed by weight gain attributable to oxidation, and culminating in intense combustion. The mass change trend shifts from an initial decline to a temporary increase, ultimately resulting in a sharp loss. The heat release behavior transitions gradually from heat absorption at lower temperatures to a significant escalation in heat release intensity, with a notable enhancement in heat release capacity during the combustion phase. The evolution of the kinetic mechanism is particularly crucial, as the activation energy increases incrementally with rising temperature. The reaction mechanism transitions from a multi-molecular layer model in the low-temperature region, through a medium-temperature contraction reaction mode, and ultimately to a high-temperature, two-stage kinetic dominance. This progression reveals the chain reaction nature of coal spontaneous combustion, transitioning from physical adsorption to the breaking of chemical bonds. This research establishes a foundational mechanism for the precise prevention and control of spontaneous combustion in abandoned coal areas within goaf regions.

Keywords: Spontaneous combustion of coal; Chromatographic oxygen absorption; Thermogravimetric-differential scanning calorimetry; Kinetic mechanism

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Corresponding author: Wenshuai Zhao., Master's degree candidate, College of Coal Engineering, Shanxi Datong University. Research direction: Unconventional oil and gas geology.

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1 Introduction

Coal seam spontaneous combustion is a significant hazard that has long plagued the global coal industry. Its detrimental effects are evident not only in the substantial waste of resources and threats to the safety of underground personnel but also in the damage it causes to production equipment. Furthermore, this phenomenon poses serious challenges to regional and even global ecosystems due to its continuous emission of large quantities of greenhouse gases (such as CO2 and CH4) and toxic pollutants (including CO and SO2). Currently, the combined application of thermogravimetric analysis (TGA/DTG) and differential scanning calorimetry (DSC) has gained significant traction in the staging and kinetic characterization of coal spontaneous combustion processes. Gao Wei-min and his colleagues discovered that the spontaneous combustion process of coal exhibits multi-stage characteristics. Notably, lean coal, characterized by its low volatile matter content and high fixed carbon content, shows that its oxidation reactions predominantly occur within the medium-to-high temperature range. Furthermore, the activation energy required for these reactions is significantly higher than that of medium- to low-rank coal types. Wen Hu et al. further noted that high-rank coal, similar to lean coal, exhibits a higher characteristic temperature and a lower peak heat release. Additionally, an increase in oxygen concentration can significantly enhance its reaction intensity. Although thermogravimetric analysis has been extensively used to investigate spontaneous combustion in lean coal, the conventional stage division of this phenomenon remains limited to a static characterization. Moreover, kinetic analyses often rely on a single reaction model and assume constant activation energy, which does not adequately account for the observed variations in activation energy with temperature. Addressing the prevention and control challenges associated with spontaneous combustion of coal in high-gas mines, current research often overlooks the complex goaf environment—characterized by competitive adsorption between gas and oxygen and the presence of air leakage fields—as well as the pronounced susceptibility to spontaneous combustion inherent in certain coal types. This oversight complicates the application of theoretical findings to effective prevention and control strategies. Therefore, this paper elucidates the mechanism of chain reaction evolution related to lean coal spontaneous combustion through a dynamic analysis of the entire process, establishing correlations with practical engineering scenarios.

2 Identification of the Spontaneous Combustion Tendency of Coal Seams

2.1 Overview of Working Face 1307

The 1307 working face is located within the #3 coal seam of the first panel area of the mine. It utilizes a fully mechanized top coal caving mining process with a coal caving height of 4 meters. The geological conditions of this coal seam are stable, featuring a gentle inclination of 3° and a thickness ranging from 4.60 to 6.10 meters, with an average thickness of 5.5 meters. The coal quality is classified as lean coal and exhibits a relatively simple structural composition.

The design parameters for the working face are as follows: the cycle progress measures 0.8 meters; the strike recovery length extends to 2,084 meters; the dip length reaches 233 meters; and the recoverable reserves amount to approximately 3.194 million tons.

2.2 Spontaneous Combustion Tendency Identification Method

The tendency of coal to undergo spontaneous combustion reflects its ability to react with oxygen at ambient temperatures, directly influencing the likelihood of such combustion. This characteristic is primarily affected by several factors, including coal composition, degree of metamorphism, internal pore structure, moisture content, sulfur content, and the mineral composition of the coal rock. Coal with a lower degree of metamorphism typically contains a higher concentration of reactive functional groups and more developed internal porosity, resulting in an increased propensity for spontaneous combustion. Through experimental measurement of characteristic temperature points and gas product generation patterns from various coal samples, coals can be classified into three categories: easily spontaneously combustible, spontaneously combustible, and not easily spontaneously combustible. This classification serves as a crucial guide for formulating and implementing fire prevention and extinguishment strategies in coal mines and provides an essential experimental foundation for future research.

The chromatographic oxygen absorption method, based on Langmuir's monolayer adsorption theory, offers a scientific classification of coal's spontaneous combustion tendency. This method measures the amount of physically adsorbed oxygen on 1 gram of dried coal sample under standard conditions (30 °C, 101,325 Pa) and incorporates key parameters such as dry ash-free volatile matter and total sulfur content. It categorizes the spontaneous combustion propensity of coal into three distinct levels: non-spontaneous combustion, spontaneous combustion, and easy spontaneous combustion. Among these classifications, the amount of adsorbed oxygen serves as a direct indicator of the coal's oxidation activity; the volatile matter content reflects the degree of metamorphism the coal has undergone; and the sulfur content influences catalytic oxidation processes. The combined assessment of these three indicators improves both the accuracy and reliability of classification outcomes, thereby providing essential theoretical foundations and technical support for fire prevention and control efforts in coal mines. Specific classification standards are detailed in Tables 1 and 2.

Samples were collected from locations characterized by normal geological structures at the 1307 working face. Three sampling points were strategically arranged in the center of the working face, each positioned 10 meters away from both the intake and return airways, as illustrated in Figure 1. The experiment was conducted using a coal spontaneous combustion tester under the following conditions: the column oven temperature was maintained at a constant 30°C to simulate standard environmental conditions, while the heat conduction temperature was kept between 80 and 100°C. The flow rates of both the carrier gas (high-purity nitrogen) and the adsorbed gas (high-purity oxygen) were set to predetermined values. Additionally, the coal sample adsorption process lasted 20 minutes to ensure adequate reaction time. A blank control, consisting of a 5-minute empty tube adsorption period, was also implemented.

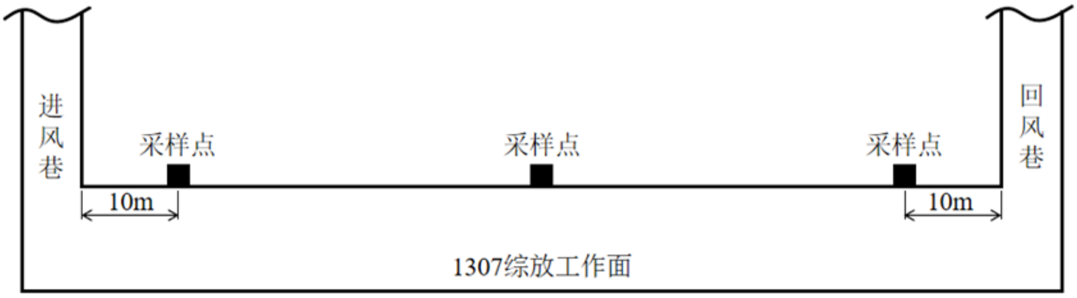


Figure 1 Schematic diagram of sampling point locations

Table 1 Classification of spontaneous combustion tendency when the volatile matter content on a dry ash-free basis (Vdaf) of the coal sample is greater than 18%

Spontaneous combustion tendency level	Spontaneous combustion tendency	Oxygen absorption capacity of coal (cm3/g) for dry coal
I	Highly flammable	Vd > 0.70
II	spontaneous combustion	0.40 < Vd ≤ 0.70
III	Not prone to spontaneous combustion	Vd ≤ 0.40

Table 2 Classification of spontaneous combustion tendency when the volatile matter content on a dry ash-free basis (Vdaf) of coal samples is ≤ 18%

Spontaneous combustion tendency level	Spontaneous combustion tendency	Oxygen absorption capacity of coal (cm^3/g) for dry coal	Total sulfur content
I	Highly flammable	Vd > 0.70	≥ 2.00
II	spontaneous combustion	0.40 < Vd ≤ 0.70	
III	Not prone to spontaneous combustion	Vd ≤ 0.40	< 2.00

2.3 Spontaneous Combustion Tendency Assessment Results

The identification results are presented in Table 3. The oxygen absorption capacity of Coal Seam 3# was determined to be 1.01 cm^3/g (for dried coal samples) using the chromatographic oxygen absorption method. According to the criteria outlined in the “Chromatographic Oxygen Absorption Identification Method for Coal Spontaneous Combustion Tendency,” this coal seam is classified as Class I in terms of its spontaneous combustion tendency, indicating a high susceptibility to spontaneous combustion. This finding provides a critical basis for developing subsequent measures to prevent spontaneous combustion within the goaf.

Table 3 Identification results of spontaneous combustion tendency of 3# coal seam in 1307 working face using chromatographic oxygen absorption method

Coal sample location	Volatile matter on a dry ash-free basis (Vdaf, %)	Oxygen uptake (cm3/g) for dry coa	Grade	Spontaneous combustion tendency
10 meters from the return air duct	38.45	1.03	I	Prone to spontaneous combustion
central section	38.26	1.01	I	Prone to spontaneous combustion
10 meters from the air intake tunnel	38.11	0.99	I	Prone to spontaneous combustion
average	38.27	1.01	I	Prone to spontaneous combustion

3 Thermogravimetric Experimental Study on Coal Spontaneous Combustion Characteristics

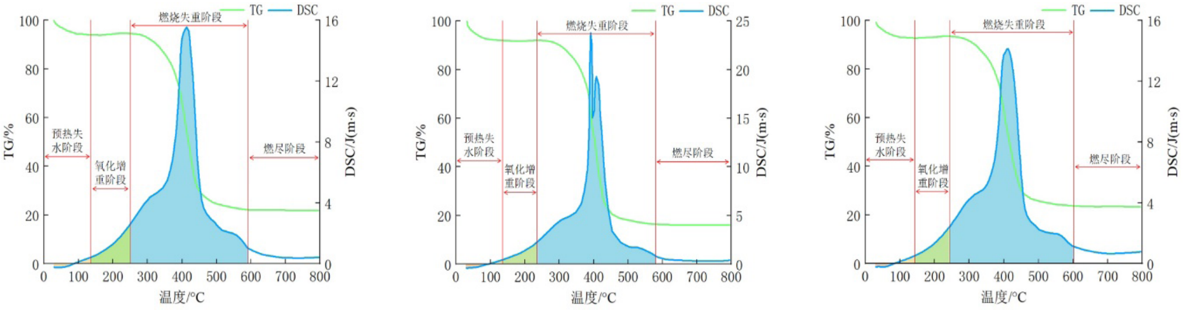
Coal spontaneous combustion is a complex dynamic oxidation process fundamentally characterized by the reaction of coal with oxygen, progressing from slow oxidation to accelerated oxidation, and ultimately resulting in exothermic combustion. The core mechanism underlying this phenomenon involves the interaction between coal and oxygen, which generates gaseous oxides and releases heat. When the rate of heat generation exceeds the capacity for heat dissipation, the temperature of the coal mass continues to rise, eventually leading to spontaneous combustion. Thermogravimetric analysis (TGA) provides an effective method for investigating this process. By monitoring real-time changes in mass (TG curve) and thermal behavior (DSC curve) of coal samples under controlled, programmed temperature conditions, it is possible to accurately determine the kinetic parameters associated with the oxidation reaction.

This method offers several significant advantages. First, it enables the simulation of the temperature evolution process associated with coal spontaneous combustion through a programmed temperature increase. Second, the thermogravimetric (TG) curve accurately reflects mass loss characteristics across various temperature ranges, while the differential scanning calorimetry (DSC) curve directly illustrates the thermal effects of the reaction. Most importantly, by conducting kinetic analysis on these curves, key parameters such as the pre-exponential factor (A) and activation energy (E) can be derived, thereby quantitatively characterizing the oxidation activity of coal.

During the experiment, the sample is gradually heated from room temperature to the target temperature at a constant rate, while the computer automatically records both mass and heat flow signals. These data not only elucidate the oxidation characteristics of the coal sample but also provide a theoretical foundation for predicting its tendency toward spontaneous combustion under real-world conditions.

3.1 Thermogravimetric Experiment Method and Results

Coal samples were collected from various locations on the 1307 working face and analyzed using thermogravimetric analysis with a STA449F5 synchronous thermal analyzer. After grinding the coal samples to a particle size of 50 mesh (0.3 mm), they were heated from 30 °C to 800 °C at a rate of 5 °C/min in a mixed atmosphere of N2 (40 ml/min) and O2 (10 ml/min). By monitoring the mass and heat flow changes of 10 mg coal samples in real time, we obtained the TG-DSC coupled curve, as shown in the figure below. Key parameters, such as characteristic temperature points and reaction enthalpy changes, were analyzed using Origin software, enabling a systematic investigation of the oxidation and spontaneous combustion characteristics of the coal seam at this working face. This study provides experimental evidence to identify and prevent areas susceptible to spontaneous combustion hazards.



1307工作面距进风巷10m煤样热重曲线图

1307工作面距中部煤样热重曲线图

1307工作面距回风巷10m煤样热重曲线图

Figure 2 Thermogravimetric curve of coal sample from working face 1307

3.2 Thermogravimetric Analysis

Further analysis and computation of the thermogravimetric experimental data elucidate the characteristic temperatures, masses, and mass losses associated with various stages of spontaneous combustion in coal samples collected from different locations on the 1307 working face, as shown in Tables 4 and 5.

Based on the analysis of Tables 4 and 5, it is evident that the coal sample located 10 meters from the air intake roadway exhibits a characteristic four-stage behavior. During the preheating and dehydration stage (29.1–135.1 °C), the coal sample primarily undergoes a physical dehydration process, with the maximum rate of water loss occurring at 54.3 °C. The mass loss during this phase amounts to 6.01%, reflecting the removal of free water as well as some bound water within the coal matrix. Upon entering the oxygen absorption and weight gain oxidation stage (135.1–249.7 °C), an oxidation reaction between the coal sample and oxygen begins. The peak rate of weight gain occurs at 200.2 °C, resulting in an overall mass increase of 0.43%. This indicates that active functional groups in the coal form unstable oxides upon interacting with oxygen. As temperatures increase into the combustion stage (249.7–592.1 °C), intense oxidative decomposition reactions occur within the coal sample, with the maximum combustion rate observed at 413.2 °C. During this phase, a significant mass loss of 72.25% is recorded, corresponding to the complete combustion of the organic matter present in the coal. Finally, beyond 592.1 °C, we reach what can be termed the burnout stage; here, a residual ash content of 22.17% indicates that a substantial proportion of non-combustible minerals remains within the coal sample.

Table 4 Characteristic temperature values of different stages of spontaneous combustion

Coal sample location	Maximum water loss rate/℃	Starting Point for Weight Gain During Oxygen Inhalation /℃	Maximum oxygen uptake rate/℃	Ignition temperature/℃	Maximum burning rate/℃	Burnout temperature/℃
10 meters from the return air duct	54.3	135.1	200.2	249.7	413.2	592.1
central section	50.1	135.8	186.3	235.4	385.8	580.3
10 meters from the air intake tunnel	53.9	144.7	196.4	242.8	416.7	602.1
average	52.8	138.5	194.3	242.6	405.2	591.5

Table 5 Mass and loss of mass during different stages of spontaneous combustion

Coal sample location	Preheating and water loss stage		Oxygen inhalation and weight gain stage		combustion phase	
	quality/%	qualitative change/%	quality/%	qualitative change/%	quality/%	qualitative change/%
10 meters from the return air duct	93.99	6.01	94.42	0.43	22.17	72.25
central section	91.96	8.04	92.54	0.58	16.57	75.97
10 meters from the air intake tunnel	92.73	7.27	93.48	0.75	23.73	69.75
average	92.89	7.11	93.48	0.59	20.82	72.66

The preheating and water loss stage of the coal sample from the middle section of the 1307 working face occurs within a temperature range of 31.8 to 135.8 °C. The maximum rate of water loss is observed at 50.1 °C, resulting in a total mass loss of 8.04% during this phase. The oxygen absorption and weight gain oxidation stage takes place between 135.8 and 235.4 °C, with the weight gain rate peaking at 186.3 °C, leading to an overall mass increase of 0.58%. The combustion stage is identified from 235.4 to 580.3 °C, characterized by a maximum combustion rate at 385.8 °C, which results in a significant mass loss of 75.97% during this period. Temperatures above 580.3 °C mark the onset of the burnout stage, with ash content constituting the remaining mass at approximately 16.57%.

The preheating and water loss stage of the coal sample, located 10 meters from the return air roadway, occurs within a temperature range of 31.4 to 144.7 °C. The maximum rate of water loss is observed at 53.9 °C, during which the mass loss reaches 7.27%. The oxygen absorption and weight gain oxidation stage occurs between 144.7 and 242.8 °C, with the peak rate of weight gain at 196.4 °C, resulting in an overall mass increase of 0.75%. The combustion stage occurs within a temperature range of 242.8 to 602.1 °C, with the maximum combustion rate observed at 416.7 °C. During this phase, there is a significant mass loss of approximately 69.75%. Beyond a temperature of 602.1 °C, the process enters the burnout stage, leaving behind an ash residue that constitutes approximately 23.73% of the original mass.

3.3 Heat Release Analysis

Differential Scanning Calorimetry (DSC) is a thermal analysis technique that depends on precise temperature measurements. The fundamental principle of DSC involves dynamically compensating for the temperature difference between a coal sample and a reference material under controlled, programmed heating. This compensation allows for the accurate determination of the energy difference required to maintain thermal equilibrium between the two. This energy difference serves as an indicator of the endothermic and exothermic reactions occurring in the coal sample during the heating process. Thermogravimetric analysis of coal samples collected from various locations on the 1307 working face revealed that their DSC curves exhibit three distinct exothermic stages: preheating and water loss, oxygen absorption accompanied by weight gain, and combustion. The peak area for each stage represents the total heat released during that phase.

By integrating the Differential Scanning Calorimetry (DSC) curves of coal samples collected from various locations along the working face's X-axis using Origin software, significant differences in heat release and absorption behaviors at different stages were observed. In the initial phase of preheating and water loss (indicated by the light orange-yellow shaded area), the coal samples exhibited endothermic behavior due to water evaporation and partial volatilization, resulting in a negative heat release rate. Subsequently, they transitioned into the preheating and water loss heat release stage (represented by the light yellow shaded area), during which the coal samples began to release heat, leading to a positive heat release rate. The amount of heat released increased significantly during the oxidation and weight gain stage (depicted by the green-filled area), reflecting an intense oxidation reaction between coal and oxygen. In the combustion and weight loss stage (illustrated by the blue filled area), the heat release rate rose rapidly, reaching a peak before declining sharply. The total heat released during this stage was notably greater—approximately 12 to 15 times that of the preceding stages—indicating complete combustion of coal with substantial energy output. The parameters related to heat release at various stages are summarized in Table 6.

Table 6 Heat release during different stages of coal sample spontaneous combustion

Coal sample location	Preheating water loss J/g	Weight gain per gram (J/g) during oxygen inhalation	Combustion stage J/g	Transition point temperature °C
10 meters from the return air duct	3.47	143.31	1781.74	85.63
central section	1.07	117.36	1855.01	89.25
10 meters from the air intake tunnel	6.43	134.34	1761.65	79.50
average	3.66	131.67	1799.47	84.79

3.4 Thermokinetic Analysis

$$\text{煤}\ S(s) + \text{空气}\ A(\mathrm{g}) \rightarrow \text{氧化煤}\ P(s) + \text{反应气体}\ B(\mathrm{g})$$

The kinetic process of coal oxidation is illustrated in Formula 1. A single heating rate, non-isothermal experimental method is employed to investigate the dynamic temperature evolution over time during the programmed temperature oxidation of coal samples. This method involves performing mathematical transformations on both the differential and integral forms of the kinetic equation to construct various linear equations, followed by using a pattern-matching approach to identify the most probable mechanism function.

The specific steps involve using kinetic analysis methods to substitute potential reaction mechanism functions—either in differential form, $f(\alpha)$, or integral form, $G(\alpha)$—into linear equations. Through linear regression analysis, key kinetic parameters, such as the activation energy (E) and the pre-exponential factor (A), are determined by examining the slope and intercept of the fitted line. The model exhibiting the best linear correlation is then selected as the most likely reaction mechanism. Since the integral method requires complex approximations of temperature integrals that may introduce significant errors, we choose the differential method for calculations to improve accuracy in kinetic analysis, as demonstrated in Formula 2:

$$d\alpha / dT = k\,f\left(\alpha\right)$$

In the formula, α represents the conversion rate of coal sample combustion decomposition (%); T denotes the temperature (K); and f(α) signifies the correlation function of the coal reaction fraction. Since the kinetic control region is defined as the area where the combustion process of coal samples occurs on the working surface during thermogravimetric experiments investigating coal spontaneous combustion characteristics, the effect of oxygen diffusion can be considered negligible. Based on Arrhenius' law, the oxidation reaction rate for the aforementioned coal sample can be expressed as:

$$\frac{d\alpha}{d\tau} = k \cdot f\left(PO_2\right) = k_0 \exp\left[-\frac{E}{RT}\right] \cdot f\left(\alpha\right) \cdot f\left(PO_2\right)$$

In the formula, τ represents the reaction time (s); f(PO2) denotes the correlation function of oxygen partial pressure; k0 stands for the frequency factor; E signifies the activation energy (KJ/mol); and R is the gas constant, valued at 8.314 J/mol. Based on the Freeman-Carroll hypothesis:

$$f\left(\alpha\right) = \left(1-\alpha\right)^n$$

In the formula, n represents the reaction order. This study employs a programmed temperature rise method to simulate the non-isothermal combustion process of coal samples, replacing the actual combustion temperature increase rate with a predetermined rate. The relationship between temperature (T) and time (τ) is linear and expressed as T=T0+βτ. In coal combustion experiments conducted under flowing air conditions, the continuous supply of oxygen ensures that the partial pressure of oxygen (PO2) in the reaction environment remains constant; therefore, f(PO2) can be treated as a constant. Consequently, Equation 5 is derived:

$$\frac{d\alpha}{dT} = \frac{A}{\beta}\exp\left(-\frac{E}{RT}\right) f\left(\alpha\right) = \frac{A}{\beta}\exp\left(-\frac{E}{RT}\right)\left(1-\alpha\right)^n$$

In the formula, β represents the heating rate (K/min), while A denotes the pre-exponential factor (s^{-1} or min^{-1}). By considering the first term of its deformation series, we obtain:

$$\ln\left[-\frac{\ln\left(1-\alpha\right)}{T^2}\right] = \ln\left[\frac{AR}{\beta E}\left(1-\frac{2RT}{E}\right)\right] - \frac{E}{RT} \qquad \left(n=1\right)$$

$$\ln\left[\frac{1-\left(1-\alpha\right)^{1-n}}{T^2\left(1-n\right)}\right] = \ln\left[\frac{AR}{\beta E}\left(1-\frac{2RT}{E}\right)\right] - \frac{E}{RT} \qquad \left(n \neq 1\right)$$

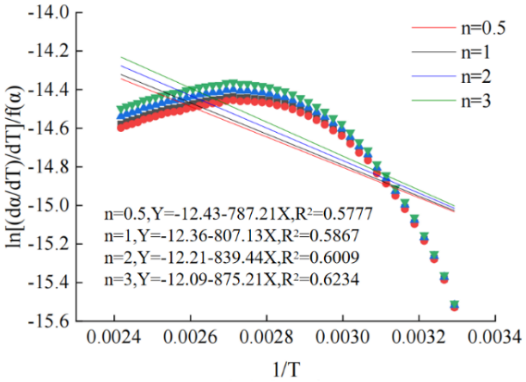
Generally, the parameter is considered a constant. By appropriately selecting the parameters $Y = \ln\left[-\frac{\ln\left(1-\alpha\right)}{T^2}\right]$, $X = \frac{1}{T}$, $a = \ln\left[\frac{AR}{\beta E}\left(1-\frac{2RT}{E}\right)\right]$, $b = -\frac{E}{R}$, or $Y = \ln\left[\frac{1-\left(1-\alpha\right)^{1-n}}{T^2\left(1-n\right)}\right]$, from this, we can derive a simplified thermokinetic equation: $Y = a + bX$. This equation enables the calculation of the activation energy (E) and the pre-exponential factor (A), which in turn facilitates the determination of the reaction mechanism function f(α) for the coal sample.

Thermogravimetric experimental data from coal samples collected at various stages and locations were subjected to linear fitting using Origin software. The intercept and slope obtained from the fitted curves provide essential parameters that can be used for subsequent thermokinetic analysis.

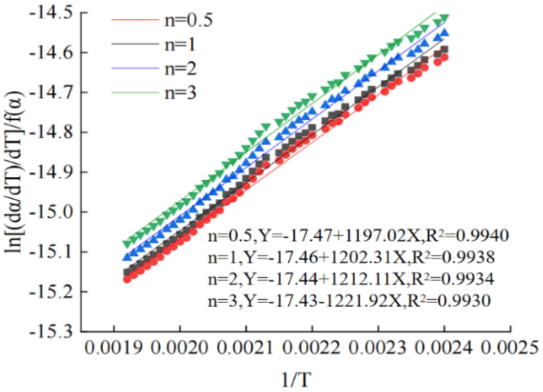
3.5 Thermokinetic Analysis of Coal Samples from Various Stages and Locations

The fitted curves of ln[(dα/dT)/f(α)] plotted against 1/T for coal samples collected from various stages—10 meters into the intake roadway, the central section, and 10 meters into the return roadway within working face 1307—are presented in Figure 3.

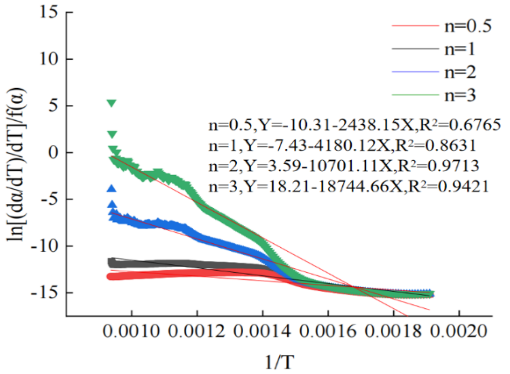
During the preheating and water loss stage of the 1307 working face intake roadway, a fitting curve with n=3 was selected at a distance of 10 meters, demonstrating an excellent fit. The specific parameters obtained were $R^2=0.6234$ and $Y=-12.09 - 875.21X$. From this data, it was calculated that E=7.2765 kJ/mol and ln A=-3.6184. During the oxygen absorption and weight gain stage, a fitting curve with n=0.5 was selected, which demonstrated an excellent fit. The specific parameters for this stage were $R^2=0.9940$ and $Y=-17.47 + 1197.02X$. Consequently, the activation energy (E) was calculated as 9.9520 kJ/mol, and ln A was determined to be -8.7578. During the combustion stage, a fitting curve with n=2 was selected, again demonstrating an excellent fit with the specific data as follows: $R^2=0.9713$ and $Y=3.59-10701.11X$. Consequently, it can be determined that E equals 88.9690 kJ/mol, while ln A is equal to 14.3781.



(a) Water loss and weightlessness stage



(b) Oxidation weight gain stage

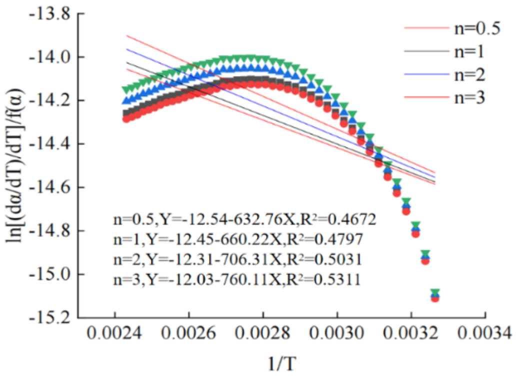


(c) Combustion weight loss stage

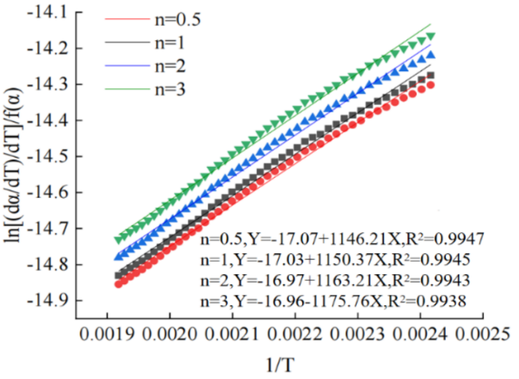
Figure 3 Fitting curve diagram of coal sample spontaneous combustion at a distance of 10m from the intake roadway on working face 1307

During the preheating and water loss stage of the coal sample from the middle section of working face 1307, a fitting curve with n = 3 was selected, demonstrating an excellent fit. The specific data are as follows: $R^2 = 0.5311$, $Y = -12.03 - 760.11X$. From this, it can be calculated that $E = 6.3196$ kJ/mol and $\ln A = -3.7113$. During the oxygen absorption and weight gain stage, a fitting curve with n = 0.5 was selected, which demonstrated an excellent fit. The specific data for this stage are: $R^2 = 0.9947$, $Y = -17.07 + 1146.21X$. From this, it can be determined that $E = 9.5296$ kJ/mol and $\ln A = -8.2983$.

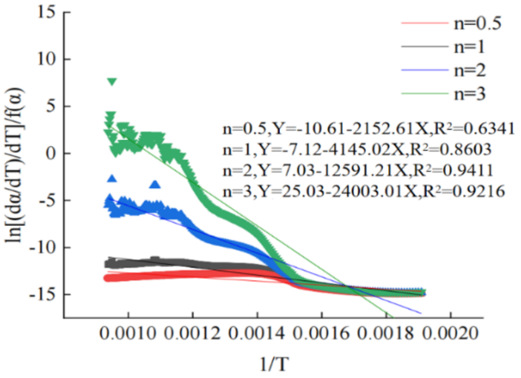
During the combustion stage, a fitting curve with n = 2 was selected, again demonstrating an excellent fit to the data collected in this phase: $R^2 = 0.9411$, $Y = 7.03 - 12591.21X$. Consequently, we find that $E = 104.6833$ kJ/mol and $\ln A = 18.0544$.



(a) The stage of water loss and weight loss



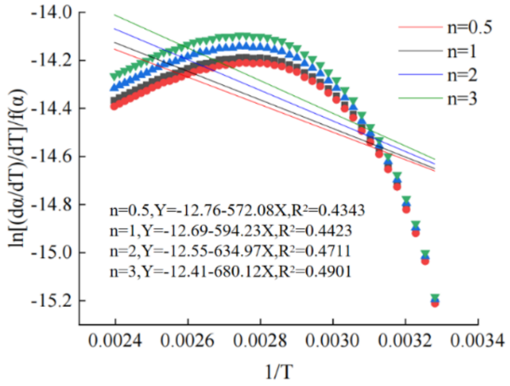
(b) Oxidation weight gain stage



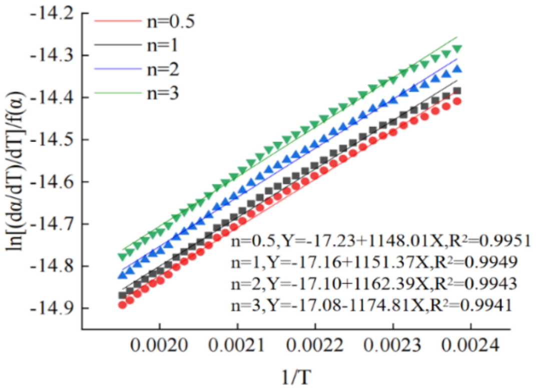
(c) Combustion weight loss stage

Figure 4 Fitting curve diagram of spontaneous combustion of coal samples in the middle of the 1307 working face

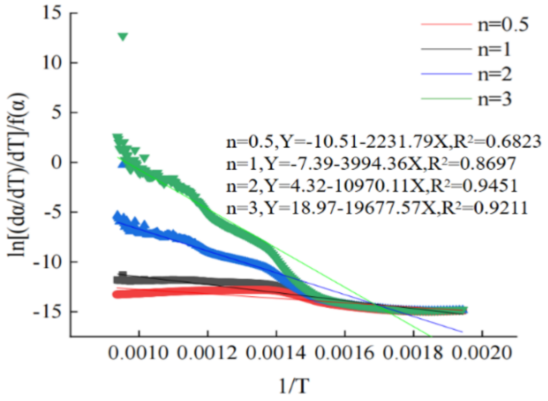
During the preheating and water loss stage of the 10 m coal sample obtained from the return air roadway of working face 1307, an excellent fit was achieved with n = 3. The specific parameters are as follows: R² = 0.9401, Y = -12.41 - 680.12X, which allows for the calculation of E = 5.6545 kJ/mol and ln A = -4.1372. During the oxygen absorption and weight gain stage, a high-quality fitting curve was obtained with n = 0.5, yielding the following specific data: R² = 0.9951 and Y = -17.23 + 1148.01X. From this, the activation energy (E) was calculated as 9.5446 kJ/mol, and the natural logarithm of the pre-exponential factor (ln A) was determined to be -8.3426. During the combustion stage, an excellent fitting curve was established with n = 2. The relevant data are as follows: R² = 0.9451, Y = 4.32 - 10,970.11X, leading to calculations of E = 91.2055 kJ/mol and ln A = 15.1623.



(a) The stage of water loss and weight loss



(b) Oxidation weight gain stage



(c) Combustion weight loss stage

Figure 5 Fitting curve diagram of coal sample spontaneous combustion at a distance of 10m from the return air roadway on working face 1307

Table 7 presents detailed data on the oxidation reaction parameters for coal samples collected from various locations on the 1307 working face during the three stages of the oxidation process. Analysis of this table indicates that the oxidation behavior of coal samples at the 1307 working face exhibits distinct characteristics across different stages: the preheating and dehydration stage follows a third-order reaction kinetics model; the oxygen absorption and weight gain stage is characterized by a shrinkage reaction mechanism; and the combustion stage follows second-order reaction kinetics. This transition in mechanisms specific to each stage reflects changes in the dominant reaction types within varying temperature ranges throughout the spontaneous combustion of coal.

Table 7 Reaction parameters in various stages of coal oxidation

Coal sample location	Reaction	Temperature range / ℃	Activation energy / (kJ·mol-1)	Relevance/R^2	InA/min-1	reaction order
10 meters from the return air duct	water loss	29.1~135.1	7.2765	0.6234	-3.6184	3
	oxidize	135.1~249.7	9.9520	0.9940	-8.7578	0.5
	combustion	249.7~592.1	88.9690	0.9713	14.3781	2
central section	water loss	31.8~135.8	6.3196	0.5311	-3.7113	3
	oxidize	135.8~235.4	9.5296	0.9947	-8.2983	0.5
	combustion	235.4~580.3	104.6833	0.9411	18.0544	2
10 meters from the air intake tunnel	water loss	31.4~144.7	5.6545	0.4901	-4.1372	3
	oxidize	144.7~242.8	9.5446	0.9951	-8.3426	0.5
	combustion	242.8~602.1	91.2055	0.9451	15.1623	2

4 Conclusion

This paper focuses on the 1307 working face and systematically investigates the spontaneous combustion characteristics of coal seams through field research, laboratory testing, and thermogravimetric analysis. The main conclusions are as follows:

(1)The lean coal extracted from working face 1307, as determined by the chromatographic oxygen absorption method, exhibits an average oxygen absorption capacity of 1.01 cm^3/g (see Table 3) and an average volatile matter content of 38.27% on a dry, ash-free basis. According to the standard “Chromatographic Oxygen Absorption Identification Method for Coal Spontaneous Combustion Tendency,” this coal is classified as a Class I seam, indicating a high susceptibility to spontaneous combustion and significant oxidation activity.

(2)The spontaneous combustion of lean coal exhibits significant phase transformations in both mass and energy. During the preheating and water loss stage, which occurs at temperatures between 30 and 140°C, the coal sample undergoes an average weight loss of 7.11%, reaching a peak value of 8.04%. This weight reduction is primarily due to water desorption and is accompanied by a modest heat release ranging from 1.07 to 6.43 J/g. During the subsequent oxygen absorption and weight gain stage, occurring between 140 and 250°C, the mass increases slightly by approximately 0.59%, reaching a peak value of 0.75%. This phase corresponds to the oxidation of active functional groups, during which the heat release intensity rises significantly, ranging from 117.36 to 143.31 J/g. As the process enters the intense combustion stage at temperatures ranging from 250 to 600°C, there is a dramatic mass loss of up to 72.66%, with peak values reaching 75.97%. This significant reduction results from the complete combustion of organic matter, releasing substantial heat energy measured between 1761.65 and 1855.01 J/g—accounting for over 90% of the total energy released during the process—and ultimately leaving behind an ash residue comprising approximately 16.57% to 23.73% of the original mass.

(3)The activation energy exhibits a stepwise increase with temperature: it ranges from 5.65 to 7.28 kJ/mol during the dehydration stage, rises to 9.53 to 9.95 kJ/mol in the oxidation stage, and culminates in a significant increase to between 88.97 and 104.68 kJ/mol in the combustion stage. Concurrently, the reaction mechanism evolves: the low-temperature dehydration zone (below 140°C) follows a third-order kinetic model ($R^2 > 0.94$), where physical adsorption is identified as the predominant mechanism; the medium-temperature oxidation zone (140–250°C) transitions to a contraction reaction mechanism ($R^2 > 0.99$), indicative of interfacial chemical reactions; finally, in the high-temperature combustion zone (above 250°C), second-order kinetics are observed ($R^2 > 0.94$), highlighting the chain reaction characteristics associated with chemical bond cleavage.

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