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Research Progress on Spontaneous Combustion Characteristics and Internal Influence Mechanism of Fractured Gas-bearing Coal Under Stress

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Research Progress on Spontaneous Combustion Characteristics and Internal Influence Mechanism of Fractured Gas-bearing Coal Under Stress

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Abstract： Coal gas and coal spontaneous combustion compound disasters severely restrict the safe production of coal mines. Residual coal in goafs generally undergoes dynamic gas adsorption and desorption, and is continuously subjected to overburden stress. Its spontaneous combustion behavior is jointly dominated by the coupling effect of stress and coal gas. Existing studies on coal spontaneous combustion mostly focus on single influencing factors, lacking systematic investigations into the synergistic effect of stress and adsorbed gas, which fails to reveal the compound disaster mechanism and results in insufficient theoretical support for the collaborative prevention and control of gas and spontaneous combustion in goafs. Therefore, this paper presents a literature review on the spontaneous combustion characteristics and internal influence mechanisms of fractured coal bearing gas under stress. The influences of stress, temperature and other factors on the macroscopic characteristics of coal spontaneous combustion are summarized, and the staged evolution characteristics are illustrated based on oxidation kinetics. From the microscopic perspectives of functional groups, free radicals and pore structures, the internal correlation between coal structural evolution and spontaneous combustion during heating is revealed. The synergistic evolution laws of gas desorption-seepage and coal spontaneous

combustion are summarized by combining macroscopic and microscopic results. This study clarifies the intrinsic mechanism whereby stress and adsorbed gas jointly control coal spontaneous combustion and remedies the deficiencies of single-factor research. It can provide a theoretical basis for the early warning, collaborative prevention and control of compound disasters as well as the safe and efficient mining of deep coal mines.
Keywords: Coal spontaneous combustion; spontaneous combustion mechanism; fractured gas-bearing coal under stress; multi-field coupling

Introduction

Restricted by China's energy endowment of rich coal, scarce oil and natural gas, coal has long accounted for more than 50% of primary energy consumption[1]. Underground mining dominates China's coal production, and gas and coal spontaneous combustion constitute major hazards threatening underground mine safety. Statistics show that thermokinetic disasters account for over 90% of all coal mine accidents since the 21st century, and their proportion rises with accident severity[2]. Given sustained coal demand, shallow reserves are depleting, and mining depth increases by 15–20m annually. Rising seam gas content and pressure amplify spontaneous combustion risks, leading to intertwined gas and coal fire disasters[3]. Residual coal in goafs stores adsorbed gas and bears overlying rock stress, forming a high-energy environment that facilitates subsequent gas desorption and oxidation[4]. Therefore, systematically investigating the spontaneous combustion characteristics and intrinsic mechanisms of fractured gas-bearing coal under stress bears vital theoretical and practical significance for revealing mine disaster evolution and ensuring safe underground mining.

Against the backdrop of persistent coal dominance and deepening mining, domestic and foreign scholars have conducted extensive research on mine safety yet existing studies have limitations. It is widely acknowledged that spontaneous combustion of gas-bearing coal is governed by multi-field coupling of temperature and pressure, closely linked to micro-pore evolution, competitive adsorption between methane and oxygen, and transformation of active functional groups.

From a macroscopic perspective, most research focuses on oxidation product generation, heat release and oxidation kinetic parameters. Tian Fuchao et al. carried out coupled temperature-pressure gas desorption and programmed heating oxidation tests[5], and found gas desorption accelerates low-temperature heating and advances characteristic temperatures with more CO generated; they further derived a formula for real-time methane concentration variation in goafs. Min Hao built a similarity platform for shallow gobs, and tests revealed S-shaped & inverted cone hazardous zones induced by coupled underground and surface air leakage[6]. The ventilation impact on zone width was quantified to optimize gob fire identification methods. Zhang Chun's experiments demonstrated loading accelerates coal heating and shortens spontaneous combustion cycle[7]. Zhai Xiawei compared coal heating and deformation rates under rising and constant stress, verifying stress enhances spontaneous combustion tendency of broken coal[8]. Li Hongjian revealed particle size effects on CO/CO_2 generation and oxygen consumption rates varying across oxidation stages[9]. He Manchao, Ma Haifeng performed mechanical loading tests at different temperatures to clarify combined effects of temperature and coal deformation on adsorbed gas desorption[10,11]. Cheng Jianwei proposed fractures alter coal permeability and fluid

flow regimes, accelerating oxidative heat convection[12].

From a microscopic perspective, scholars mainly analyze pore structures and functional groups. Qin et al. investigated the microscopic oxidation mechanism of oil-immersed coal through TG-in-situ FTIR tests[13]. They confirmed that crude oil inhibits low-temperature coal oxidation, with 270 °C as the threshold for functional group evolution. Methylene peaks can characterize aliphatic groups in low-oil coal, providing microscopic support for spontaneous combustion prevention in oil-coal co-occurrence mines. Li Zhenrong adopted low-temperature nitrogen adsorption, SEM and TG-FTIR combined with fractal theory[14], and revealed adsorbed methane protects micropores and suppresses reactions of oxygen-containing active groups via competitive adsorption. Li Shuaikui reviewed pore and functional group evolution under multi-gas competitive adsorption, and found heating generates interconnected micropores while CH_4/CO_2 restrain active group oxidation[15], though quantitative coupling theories remain insufficient. Jia et al. [16-17] adopted a multi-field coupling test platform to reveal the micro-mechanism of gas reactions during the three-stage coal spontaneous combustion, the bidirectional coupling disaster-inducing mechanism between gas and coal spontaneous combustion, and the inhibitory effect of adsorbed gas on coal spontaneous combustion. Li Zenghua put forward the free radical mechanism of coal spontaneous combustion, stating external force breaks covalent bonds to generate radicals prone to oxygen reaction[18]. Li Zhiqiang, Yuan Mei et al. discovered significant coupling effects of temperature and effective stress on coal permeability[19-22]. Zhang Yutao pointed out low-concentration methane delays spontaneous combustion by inhibiting two key exothermic reactions including aliphatic chain cleavage and conversion of carbonyl to carboxyl[23].

Evidently, existing studies mostly adopt thermodynamic methods to analyze separate effects of stress or adsorbed gas via characteristic temperature and heat release data, while integrated research considering combined stress and gas adsorption is scarce.

Centered on spontaneous combustion characteristics and multi-field coupling disaster mechanism of fractured gas-bearing coal under stress, this review establishes a research framework integrating macroscopic properties and microscopic evolution (Figure 1). This research follows the logic of “identifying, analyzing, solving and summarizing problems”. Existing coal spontaneous combustion studies mostly focus on single factors, while this paper targets the coupling effect of stress and adsorbed gas and puts forward three core scientific issues. A self-developed all-in-one stress-seepage-heating oxidation coupling test platform is built for multi-variable comparative tests. Combined with FTIR, EPR and other microscopic characterization technologies, competitive adsorption and mechanical fragmentation theories are integrated to reveal multi-field spontaneous combustion mechanisms from macro and micro perspectives. Featuring theoretical and experimental innovations, this study clarifies staged combustion characteristics, microstructural evolution and multi-factor coupling mechanisms of stressed fractured gas-bearing coal, supporting fire prevention in deep mine goafs.

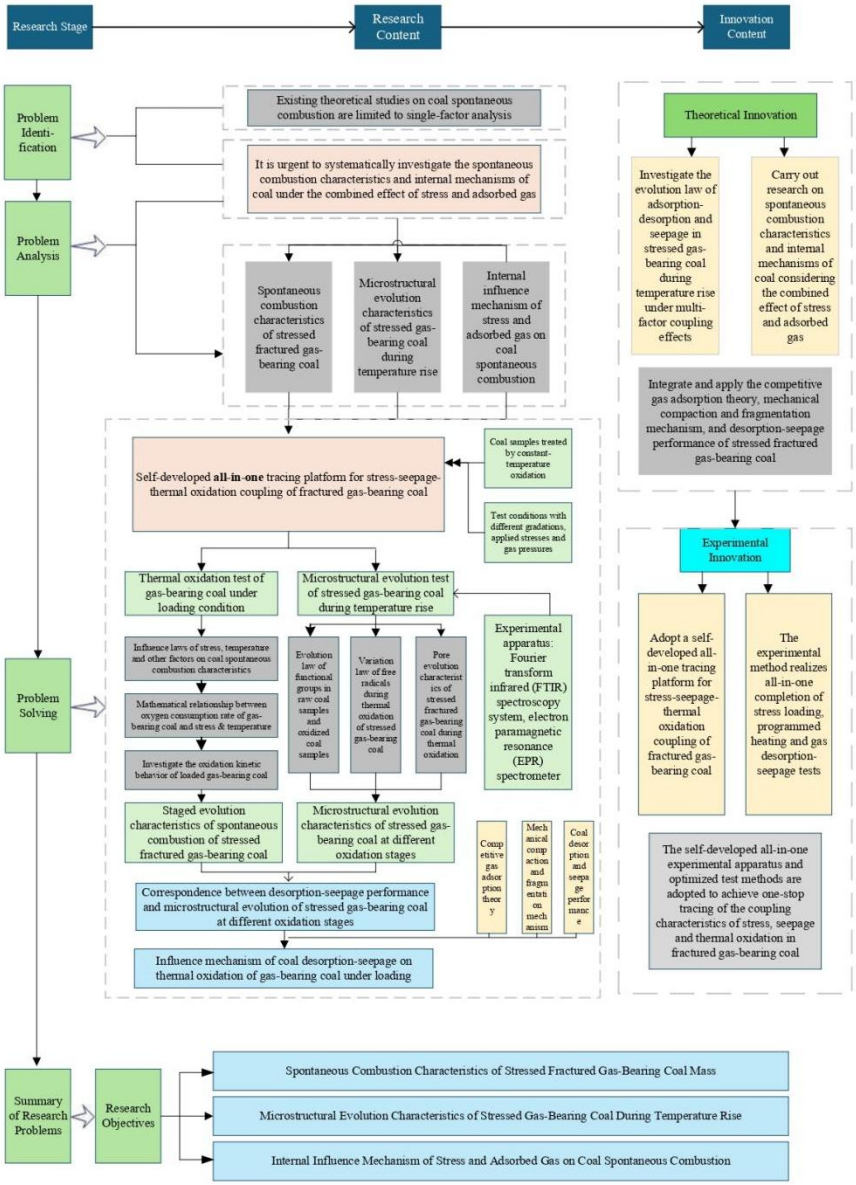


Figure 1 Technical Roadmap for Spontaneous Combustion Characteristics and Internal Influence Mechanism of Stressed Fractured Gas-Bearing Coal

1 Spontaneous Combustion Characteristics of Fractured Gas-Bearing Coal Under Stress

1.1 Spontaneous Combustion Laws of Fractured Gas-Bearing Coal Under Stress

Domestic and foreign scholars have carried out extensive macroscopic experimental studies on the spontaneous combustion laws of fractured coal under high gas pressure. Centering on characteristic parameters such as gas and heat generation, they revealed the spontaneous combustion evolution rules and quantitative mathematical relationships under the coupling of

stress, gas and temperature. Researches demonstrate that stacking structure and porosity of coal as well as oxygen supply conditions are altered under loading, which greatly regulate oxidation progress. Gas restrains reaction rate via competitive adsorption and oxygen dilution. Jointly, these two factors determine coal heat release intensity and generation characteristics of CO, CO_2 and other gases. Relevant findings lay an important experimental foundation for understanding the macroscopic spontaneous combustion rules of high-gas coal dominated by stress.

1.1.1 Advances in Experimental Platforms and Research Methods for Gas-Bearing Coal

Residual coal inside goafs accumulates as fractured masses. It stores large amounts of adsorbed gas and sustains stress from overlying strata. The bearing stress acting on residual coal varies periodically with the advance of the working face. This periodic stress fluctuation alternately compacts and loosens the broken coal, changing its porosity and permeability dynamically. Such structural variations further modify coal's gas desorption-seepage performance and oxygen adsorption capacity. To address this problem, scholars have independently developed a series of experimental apparatuses from the perspectives of stress, temperature, adsorption and desorption.

Ma Junrong et al.[24] built an independent thermal imaging test system for coal combustion and explosion. The results indicate physical reactions like gas desorption dominate the early oxidation stage, while CO, C_2H_4 and other gaseous products are gradually released as oxidation proceeds. Pan Rongkun et al.[25-26] conducted programmed heating experiments on unloading coal to explore oxidation features under different stresses. They found coal oxidation capacity presents a hump curve against initial stress, with CO output and oxidation activity peaking at the initial stress of 25 MPa after mining unloading. Hao Yu et al.[27] carried out programmed heating and thermogravimetric tests under variable gas concentrations. The results show rising gas concentration markedly increases apparent activation energy, lowers CO and CO_2 output and raises their initial generation temperature, thus inhibiting low-temperature coal oxidation. Zhai Xiaowei et al.[8] stated elevated stress compacts fractured coal and refines particles to enlarge specific surface area, greatly boosting coal oxidation activity and CO production.

Chao et al.[28] revealed under thermo-mechanical coupling, rising initial temperature and stress delay the peak heat flow temperature and reduce endothermic peaks and total heat absorption. Activation energy declines with fixed temperature while it first drops then rises under constant stress, corresponding to an initial increase followed by reduction in coal chemical activity. Wang Fei et al.[29] performed programmed heating tests and found that when methane volume fraction rises from 0 to 4%, low-temperature oxidation of weakly caking coal is significantly suppressed, with oxygen consumption rate, heat release intensity, CO and C_2H_4 output declining and apparent activation energy increasing; methane and low oxygen exert synergistic inhibitory effects on oxidation. Liu Jing[30] discovered adsorbed methane regulates low-temperature oxidation in stages: at low temperatures, methane occupies pores and active sites to hinder coal-oxygen combination, raising critical and crack temperatures and generating oxidation lag; at high temperatures, it facilitates CO generation yet restrains CO_2, C_2H_4 and C_2H_6 production, leading to obvious staged gas evolution with temperature.

Xu Yongliang et al.[31-33] adopted a loading coal spontaneous combustion tester for heating experiments and verified gas atmosphere, uniaxial stress and coal particle size are core factors

governing oxidation. 120°C is the critical temperature for fierce functional group reactions. Uniaxial stress changes pore structures and active site quantities to adjust activation energy and oxygen consumption in phases. Coals of different particle sizes share consistent variation trends of heating rate, oxygen consumption and heat release against stress and temperature; appropriate stress strengthens oxidation heat release of large-size coal. Overall, oxygen-containing functional groups, aliphatic hydrocarbons and hydroxyl groups evolve regularly with temperature. Coupling of inert atmosphere and stress jointly controls low-temperature oxidation rate, activation variation and spontaneous combustion risk of coal.

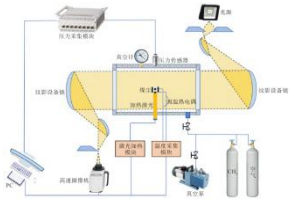
Through programmed heating and statistical analysis, Ren Wanxing et al.[34] divided coal low-temperature oxidation into fluctuation, stable and attenuation stages. The concentrations of indicator gases fit the Logistic regression model. A six-level early-warning system can be established based on the initial and inflection temperatures of CO and C_2H_4. Coal metamorphism affects gas output concentration rather than variation rules. Xu Huicong et al.[35] adopted a multi-field coupling test system integrating seepage and temperature under dynamic disturbance. Experiments show coupled stress-temperature-seepage-disturbance remarkably intensifies coal oxidation heat release, shortens spontaneous combustion induction period, develops more fractures and boosts gas emission, greatly elevating coal spontaneous combustion liability and risk. Coal failure is mainly shear-dominated with synchronous intensification of thermal effect and acoustic emission response, providing key support for multi-field coupling mechanism analysis and early warning.

Ma et al.[11] found under deep high in-situ stress and high temperature, cumulative gas desorption of coal follows a convex parabola against time with desorption rate decaying in power function. Temperature accelerates desorption while confining pressure restrains it; residual deformation stage features far higher desorption capacity and rate than other phases. Li et al.[36-37] conducted tests on self-developed platforms and proved temperature-pressure coupling strongly affects gas desorption: desorption capacity rises with pressure yet falls with temperature. The coupling of gas adsorption-desorption and low-temperature oxidation modifies coal pore structures, lowering total pore volume and specific surface area while increasing micropore/mesopore proportion and pore fractal dimension. Methane inhibits coal-oxygen reactions by occupying active sites and diluting oxygen. All experimental apparatuses mentioned are summarized in Table 1.

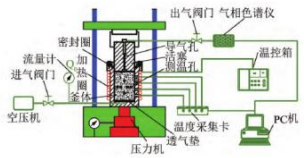
Author	Equipment Name	Research Focus	References
Ma Junrong	Multiphase Combustion & Explosion High-Speed Synchronous Imaging Test System	Desorption, Oxidation	[24]
Pan Rongkun	Oxidation Experimental Platform for Loaded Coal Mass	Stress, Oxidation	[25-26]
Hao Yu	Programmed Temperature Rise Test System for Coal Spontaneous Combustion	Oxidation	[27]
Zhai xiaowei	Experimental platform of coal oxidation under loaded.	Stress, Oxidation	[8]
Chao Jiangkun	Experimental platform of coal oxidation under loaded.	Stress,	[28]

		Oxidation	
Wang Fei	Programmed Heating Experimental Apparatus for Coal Samples with Variable Gas Contents	Oxidation	[29]
Liu Jing	Programmed Temperature Rise Experimental System for Coal Spontaneous Combustion	Adsorption, Oxidation	[30]
Xu Yongliang	Programmed Temperature Rise Experimental System for Coal Spontaneous Combustion	Stress, Oxidation	[31-33]
Ren Wanxing	Programmed Heating Experimental Apparatus for Coal Samples with Variable Gas Contents	Oxidation	[34]
Xu Huicong	Seepage-Temperature Coupling Test System under Dynamic Disturbance	Stress, Seepage	[35]
Ma Haifeng	The seepage-adsorption-desorption testsystem on coal and rock mass	Desorption, Stress	[11]
Li Shuaikui	Coupling experimental platform for gas adsorption/desorption and CSC heating and oxidation.	Stress, Oxidation	[36-37]

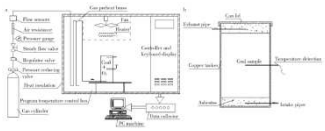
Table 1 Overview of Experimental Platforms in Previous Studies



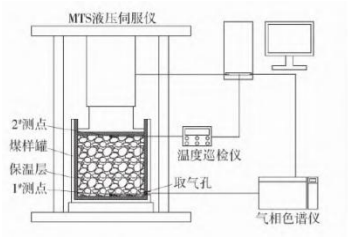
a. Multiphase Combustion & Explosion High-Speed Synchronous Imaging Test System



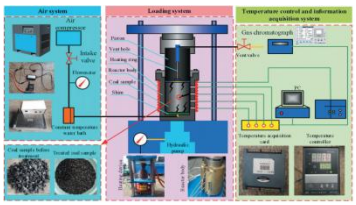
b. Oxidation Experimental Platform for Loaded Coal Mass



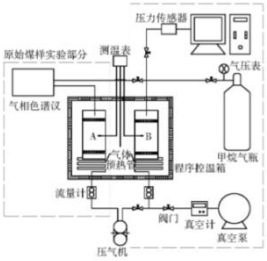
c. Programmed Temperature Rise Test System for Coal Spontaneous Combustion



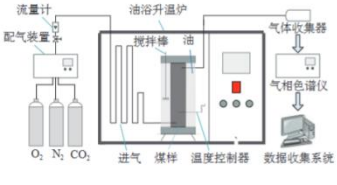
d. Experimental platform of coal oxidation under loaded.



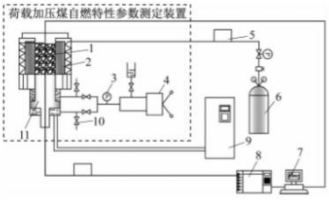
e. Experimental platform of coal oxidation under loaded.



f. Programmed Heating Experimental Apparatus for Coal Samples with Variable Gas Contents



g. Programmed Temperature Rise



h. Programmed Temperature

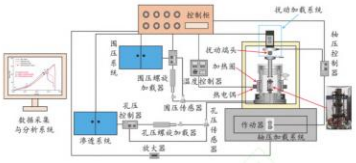


i. Programmed Heating

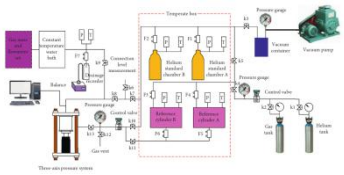
Experimental System for Coal Spontaneous Combustion

Rise Experimental System for Coal Spontaneous Combustion

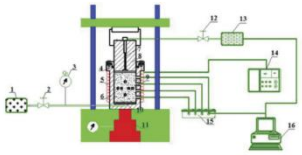
Experimental Equipment



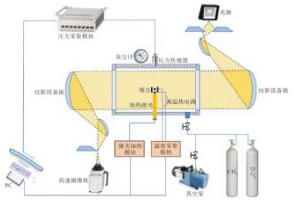
j. Seepage-Temperature Coupling Test System under Dynamic Disturbance



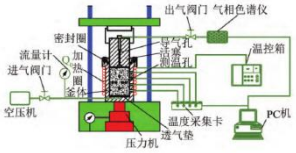
k. The seepage- adsorption-desorption testsystem on coal and rock mass



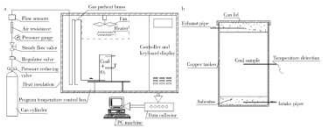
l. Coupling experimental platform for gas adsorption/desorption and CSC heating and oxidation.



a. Multiphase Combustion & Explosion High-Speed Synchronous Imaging Test System



b. Oxidation Experimental Platform for Loaded Coal Mass



c. Programmed Temperature Rise Test System for Coal Spontaneous Combustion

Figure 2 Overview of Experimental Platforms in Previous Literature

In addition, Li Zhiqiang et al.[22] investigated the influences of temperature and stress on coal permeability. They pointed out that rising temperature increases the sensitivity of permeability to effective stress; coal exhibits higher plasticity at high temperatures, which further compresses pores under loading. A permeability calculation formula under the combined effect of stress and temperature was proposed, as shown in Equation (1):

$$K(\sigma_{ef}, t) = K_z \exp(\alpha_1 t - \alpha_2 \sigma_{ef}) \quad (1)$$

In the equation, $K(\sigma_{ef}, t)$ represents Permeability variation function under the combined coupling effect of stress and temperature，$10^{-3}\mu m^2$；K_z represents the Theoretical initial permeability while t=0 □σ_{ef} =0, $10^{-3}\mu m^2$；t represents temperature , ºC；α_1, α_2 represents experimental fitting coefficients；when $\sigma_t > \sigma_{ef}$,□α_1 >0□and α_2 >0；when $\sigma_t < \sigma_{eff}$, α_1 <0□and α_2 >0；σ_t represents thermal stress,□MPa；σ_{ef} represents effective stress,□MPa。。Wang Xiaoyan et al.[38] carried out programmed heating, simultaneous thermal analysis and FTIR tests. The results reveal that rising methane concentration markedly elevates the initial generation temperatures of oxidation products , while the gas generation rate and oxygen consumption rate decrease monotonically at all temperature stages, accompanied by reduced heat release and a prominent increase in apparent activation energy for low-temperature oxidation.

The experimental apparatuses developed and regular conclusions obtained by the above scholars fully demonstrate that a systematic research achievement system has been established regarding the seepage, adsorption-desorption and oxidation characteristics of coal under the multi-field coupling of stress, temperature and gas, which also lays solid experimental foundations and theoretical support for subsequent research. Nevertheless, obvious deficiencies still exist in

current experimental devices and relevant studies. Most test apparatuses are only designed for single-factor or two-field coupling tests, such as merely investigating the influence of stress on oxidation, temperature on seepage, or gas on adsorption-desorption. There is a lack of integrated experimental platforms capable of realizing synchronous multi-field and multi-process coupling of "stress-temperature-gas-oxidation". Such single-factor-oriented research modes cannot truly reflect the complex in-situ conditions of coal in underground goafs subjected to the simultaneous combined effects of in-situ stress, mining disturbance, temperature field and gas field. Consequently, many conclusions are only applicable to specific simplified conditions and deviate from engineering practice, which restricts the in-depth understanding of the evolution mechanisms of multi-physical and chemical processes in coal under multi-field coupling.

1.1.2 Macroscopic Staged Evolution Characteristics of Coal Spontaneous Combustion

Coal oxidation and spontaneous combustion exhibit distinct staged evolution characteristics. As oxidation proceeds, different chemical reactions occur with mutual restriction among various influencing factors, forming clear staged features. Exploring such staged laws is conducive to the effective early warning and prevention of coal spontaneous combustion disasters.

1.1.2.1 Thermal Oxidation Characteristics During Temperature Rise

Through programmed heating experiments, scholars have reached a consensus that coal spontaneous combustion possesses prominent staged characteristics. With rising coal temperature, characteristic parameters including the generation rate of gaseous products, oxygen consumption rate, functional group content and activation energy show staged variations at specific critical temperatures. Zhao Jingyu et al.[39] divided the spontaneous combustion process of weathered coal by temperature into two stages: the low-temperature oxidation stage dominated by hydroxyl groups (below 200°C) and the medium-high temperature oxidation stage dominated by aliphatic hydrocarbons (200~400°C), where the reaction progress is governed by different functional groups in each stage. Taking 60°C as the critical temperature and 150°C as the cracking temperature as dividing points, Li Xuping et al.[40] classified bituminous coal oxidation under alkaline environments into three stages, and revealed that the alkalinity intensity exerts differentiated regulatory effects on the activation energy and reaction rate of each stage. Taking 40°C and 120°C as key critical temperatures, Li Jianxin et al.[41] subdivided coal low-temperature oxidation into the initial low-temperature stage, slow oxidation stage and accelerated oxidation stage. The study concluded that abnormal emission of indicator gases originates from differentiated oxidation pathways of active groups on coal surfaces. Physical adsorption and weak oxidation dominate the low-temperature stage; rapid reactions of oxygen-containing functional groups in the medium-temperature stage trigger sharp surges of CO and CO_2; cleavage of aromatic structures at high temperatures leads to exponential growth of gas production, revealing the correlation between abnormal indicator gas release and microscopic group fracture. Shi Jianxiang et al.[42] set 70°C and 130°C as demarcation points to divide the whole coal spontaneous combustion process into three stages: slow oxidation, accelerated oxidation and intense oxidation. It was found that oxygen consumption rate, gas production rate and heat release intensity increase gradually with temperature. The oxidation rate rises remarkably after 70°C, and coal enters the rapid spontaneous combustion stage above 130°C, with limit parameters varying regularly throughout oxidation, providing critical temperature thresholds for early monitoring and early warning of coal

spontaneous combustion. Combining programmed heating tests with ReaxFF molecular dynamics simulations, Liu Yao et al.[43] investigated the spontaneous combustion characteristics and microscopic mechanisms of lignite, gas coal and fat coal under various oxygen concentrations. Taking 100°C and 150°C as key critical temperatures, coal spontaneous combustion was categorized into three stages: slow oxidation stage (below 100°C) dominated by physical coal-oxygen adsorption with low indicator gas output; accelerated oxidation stage (100~150°C) featuring massive reactions of active groups and drastically increased gas generation rate; intense oxidation stage (above 150°C) with exponentially growing gaseous products. Based on adiabatic oxidation and programmed heating tests, Zhu et al.[44] subdivided the low-temperature oxidation of coal spontaneous combustion into five periods: incubation period, heat accumulation period, evaporation period, active period and oxygen-deficient period, with critical temperatures set at 55~70°C, 90°C, 105°C and 170°C. The oxidation rate, gas production and heat release features of each period were clarified, and corresponding risk grading standards and hierarchical control measures were established, which further improved the staged early warning and prevention theory of coal spontaneous combustion.

Table 2 Statistics of Programmed Heating Oxidation Experiments

Author	Critical temperature	Stage Division	Division Basis	Reference
Zhao Jingyu	200°C、400°C	Low-temperature oxidation stage (below 200°C) , Medium-high temperature oxidation stage (200~400°C)	Functional groups	[39]
Li Xuping	60°C、150°C	Early stage (<60°C)、Middle stage (60~150°C) and Late stage (>150°C)	Activation energy	[40]
Li Jianxin	40°C、120°C	Initial low-temperature stage (30~40°C) 、Slow oxidation stage (40~120°C) 、Accelerated oxidation stage (>120°C)	Gas production rate	[41]
Shi Jianxiang	70°C、130°C	Slow oxidation stage (<70°C) 、Accelerated oxidation stage (70~130°C)、Intense oxidation stage (>130°C)	Gas production rate	[42]
Liu Yao	100°C、150°C	Slow oxidation stage（＜100°C）、Accelerated oxidation stage（100~150°C）、Intense oxidation stage（＞150°C）	Gas production rate	[43]
Zhu Hongqing	55~70°C 、90°C、105°C、170°C	Incubation period（<70°C）、Heat accumulation period （70~90°C）、Evaporation period（90~105°C）、Active period（105~170°C）、Oxygen-deficient period（>170°C）	Gas production and heat release rate	[44]

It can be seen from the table that although different scholars adopt different division criteria such as functional group evolution, activation energy variation, gas and heat release rates, they all reflect the unified staged evolution law of coal spontaneous combustion: physical adsorption →

slow oxidation → accelerated oxidation → violent combustion. Around 60°C serves as the first critical temperature. Before this temperature, physical adsorption dominates coal reactions with weak chemical oxidation; the oxygen consumption and heat release are low, and CO and other gaseous products increase gently. The coal structure remains stable without obvious heat accumulation, corresponding to the incubation and early slow self-heating stage of spontaneous combustion. The second critical temperature is approximately 130°C. Within this interval, chemical oxidation is drastically accelerated, oxygen consumption and heat release rates rise sharply, and CO, CO_2 grow exponentially. Coal begins thermal decomposition with abundant pores and active groups exposed, entering the accelerated self-heating stage accompanied by obvious heat accumulation. When the temperature exceeds this threshold, the third stage commences with fierce oxidation and pyrolysis, massive gas emission, and heat generation far exceeding heat dissipation. The temperature surges rapidly, coal undergoes cracking and combustion, and open flame and high-temperature flue gas eventually appear, marking the complete spontaneous combustion stage.

1.1.2.2 Gas Desorption Characteristics

Based on the above analysis of macroscopic staged evolution of coal spontaneous combustion, multi-scale mechanisms of gas action on coal oxidation are further explored. Deng Jun et al.[45] pointed out that methane strongly suppresses low-temperature coal oxidation by occupying adsorption sites, hindering the evolution of active groups and raising activation energy, with the optimal inhibitory concentration at 4% and a more prominent effect on high-rank coal. Zhang Tonghao et al.[46] found that pre-adsorbed methane restrains low-temperature oxidation via competitive adsorption and oxygen partial pressure dilution while increasing activation energy, and the inhibitory effect intensifies with rising gas pressure. Qin Yueping et al.[47] adopted a three-dimensional physical simulation platform and concluded from ventilation perspectives that the range of oxidation zones is jointly controlled by air leakage intensity and gas dilution; higher methane concentration dilutes oxygen and reduces oxygen consumption, thereby suppressing low-temperature oxidation. Using coupled UDEC-FLUENT numerical simulation, Zhang Xuebo et al.[48] investigated overlying strata movement, void fraction distribution and gas migration under small faults, proving that gas migration and distribution alter the scope and location of oxidation zones and further govern the initiation and development of coal fires.

Existing studies have verified that characteristic parameters of oxidation products, heat release and oxidation kinetics evolve regularly during coal spontaneous combustion. In the rapid gas desorption stage, methane displaces and dilutes oxygen in gas phase to reduce coal-oxygen contact. During slow desorption, methane and oxygen compete for physical adsorption/desorption on coal surfaces and restrict the utilization of active sites. After complete gas desorption under continuous heating, intensive chemical adsorption and oxidation reactions occur on coal surfaces to produce CO, accompanied by transformations of coal matrix functional groups, which greatly accelerates spontaneous combustion. Through physical simulation tests, Zhang Chaolin et al.[49] demonstrated that gas under deep mining undergoes staged evolution: slow desorption → massive rapid desorption → instantaneous outburst, and the desorption rate, pressure and permeability at each stage are highly coupled with coal damage and oxidation rate. Throughout the oxidation process, gas follows a three-stage pattern: steady slow desorption at low temperature, accelerated massive desorption at medium temperature, and rapid abrupt release at high temperature. Gas

desorption and seepage dynamically couple with pore evolution and oxidation rate at all stages, forming distinct phase boundaries and further verifying the prominent staged nature of coal spontaneous combustion. Therefore, gas exerts variable multi-field coupling effects on coal oxidation instead of a single fixed action, which provides crucial theoretical support for subsequent research on spontaneous combustion of fractured coal under gas and stress. The relevant characteristics are shown in Figure 3.

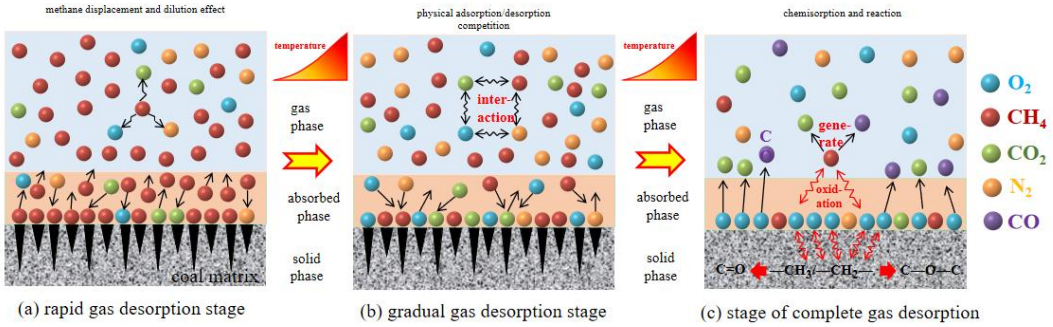


Figure 3 Staged Gas Desorption Characteristic[5]

1.2 Principles of Coal Oxidation Kinetics

At present, researchers generally regard the spontaneous combustion of gas-bearing coal as a three-stage process: slow low-temperature oxidation, self-accelerating heating and rapid combustion. Physical adsorption dominates the low-temperature stage with little heat release. As active functional groups in coal continuously participate in reactions, chemical adsorption takes over and oxidation intensifies, generating massive heat. Once heat production exceeds heat dissipation, accumulated thermal energy drives continuous temperature rise until the ignition point is reached and coal fire occurs[50-51].

The kinetic characteristics of coal oxidation are usually obtained via thermogravimetric experiments. Kinetic characterization is realized by calculating pre-exponential factors and activation energy throughout spontaneous combustion. Domestic and foreign scholars have carried out extensive targeted experiments on this core process to systematically investigate the laws and effects of key factors on oxidation reaction rates at different oxidation stages. Li Hongjian[9] conducted programmed heating experiments focused on pore structures and divided oxidation stages at 80°C. He concluded that pores mainly transport oxygen during slow oxidation below 80°C; when temperature exceeds 80°C, air provides abundant active sites and greatly raises the heating rate. Deng et al.[52] investigated co-gasification performance of binary briquettes blended with Ningdong and Taixi coal through TG-MS and fixed-bed orthogonal experiments, verified prominent synergistic effects during co-pyrolysis and obtained optimized parameters for co-production of high-performance activated carbon and hydrogen-rich syngas, which offered feasible technical routes and kinetic data support for clean utilization of low-rank coal.Through thermogravimetric analysis, Lou Hezhuang et al.[53] found that rising methane volume fraction reduces coal mass loss and heat release and slows coal-oxygen compound reaction rate. At the early spontaneous combustion stage, activation energy and pre-exponential factor slightly increase with methane concentration, while both parameters decrease with growing gas volume fraction during the coal combustion stage. Hao Yu et al.[54] stated that methane exhibits stronger competitive adsorption than oxygen in the initial physical adsorption stage and occupies active

sites, drastically lowering the initial reaction rate. After oxidation initiates, oxygen is diluted, the initial generation temperatures of CO and CO_2 rise and their yields drop sharply, leading to an obvious reduction in oxidation rate. Liu Jing et al.[30] proposed that pre-adsorbed methane exerts a two-stage effect on oxidation rates: it inhibits oxidation at low temperatures yet promotes incomplete oxidation at high temperatures. At high temperatures, nearly all methane desorbs, coal-oxygen reactions are intensified, and CO generation rate rises significantly to accelerate the oxidation process.

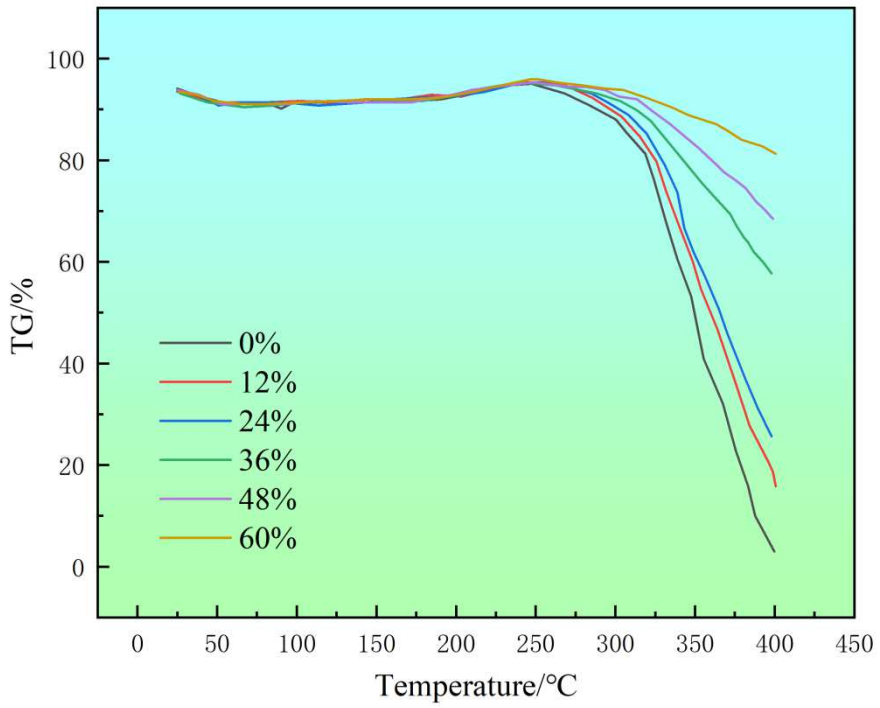


Figure 4 Thermogravimetric Curves under Different Gas Atmospheres[53]

Synchronous thermal analysis (TG-DSC) can be adopted for further experimental investigations into coal low-temperature oxidation. Researchers acquire core oxidation kinetic parameters including activation energy and pre-exponential factor via TG-DSC tests, thereby revealing the kinetic laws governing complex coal oxidation reactions.

Du Qianru et al.[55] conducted TG-DSC tests and found that the activation energy and pre-exponential factor at all low-temperature oxidation stages rise with coal metamorphic grade, and each stage follows a distinct mechanism function; higher coal rank corresponds to elevated activation energy and pre-exponential factor, meaning oxidation reactions become more difficult. Focusing on coal secondary oxidation, Ding Xuqin et al.[56] discovered that pre-oxidation within 80–160°C reduces the apparent activation energy and increases the pre-exponential factor during accelerated oxidation of bituminous coal. The activation energy reaches its minimum and reactivity peaks at a pre-oxidation temperature of 120°C, while activation energy rebounds and reactions become harder at 200°C, showing an overall decreasing-then-increasing trend. Yan Qingqiong et al.[57] also obtained from TG-DSC experiments that activation energy and pre-exponential factor grow with coal rank, attributed to the more stable molecular framework and higher aromatic condensation of high-rank coal, which demands greater energy for oxidation and raises effective molecular collision frequency.

Xie Xumin et al.[58] studied igneous intruded coal seams and proved igneous thermal action

drastically cuts activation energy and boosts pre-exponential factor of bituminous coal across all oxidation stages. The underlying mechanism lies in thermally developed pores, abundant active groups and free radicals, as well as fully exposed reaction sites, which greatly accelerate oxidation and spontaneous combustion liability. Ren Xiaoqian et al.[59] performed tests on coal samples with varying moisture contents under low-temperature alternating freeze-thaw cycles. The results show low-moisture coal has reduced activation energy and pre-exponential factor at each oxidation stage, whereas high-moisture coal exhibits higher activation energy and larger pre-exponential factor in the combustion stage. Freeze-thaw cycles expand pores in low-moisture coal to facilitate oxygen contact, while water blocks pore channels and hinders coal-oxygen combination for high-moisture coal, leading to opposite trends in reaction barrier and collision frequency.

Xiao et al.[60] took low-rank bituminous coal as the research object and employed TG-DSC to explore thermal behaviors and kinetic properties under different gas flow rates. They divided oxidation into five stages with six characteristic temperatures, and identified 150mL·min^{-1} as the optimal ventilation rate featuring the lowest apparent activation and strongest heat release; excessively high or low flow rates suppress oxidation, improving coal fire prevention theories. Jia et al.[61] combined TG-DSC and low-temperature nitrogen adsorption to compare spontaneous combustion kinetics and staged characteristics of tectonic coal and intact coal from the identical seam, categorizing five oxidation stages. Tectonic coal possesses lower activation energy and faster reaction rates in slow oxidation, while intact coal reacts more fiercely in rapid oxidation; an intersection temperature exists for their CO output and oxygen consumption, supporting differentiated fire prevention strategies.

Zhang et al.[62] adopted coupled TG-DSC-FTIR technology to analyze the effects of oxygen concentration and heating rate on coal mass variation, heat release and gaseous products, dividing oxidation into four stages where mass loss accounts for over 80% during combustion. Increased oxygen concentration accelerates oxidation and lowers characteristic temperatures, and the influence of heating rate on reaction rates varies with ignition temperature. Based on TG-DSC curves. Wang et al.[63] utilized DSC thermal analysis combined with the FWO kinetic model to investigate the differences in thermal behaviors of coal low-temperature oxidation under various CO_2 concentrations. It was verified that CO_2 exerts a far stronger inhibitory effect on the exothermic oxidation stage than the endothermic stage, and high-concentration CO_2 delays characteristic oxidation temperatures. The study clarifies the staged thermodynamic inerting mechanism of CO_2 and offers kinetic foundations for optimizing the technology of injecting CO_2 into goafs for fire prevention. Zhang Lina[64] classified coal spontaneous combustion into water-loss mass reduction, oxygen-absorption mass gain and combustion mass loss stages. The activation energy of each stage was calculated to analyze oxidation processes; rising heating rate shifts TG curves toward higher temperatures and elevates the temperatures of oxygen adsorption and ignition points, providing experimental evidence for the staged kinetic mechanism of coal spontaneous combustion.

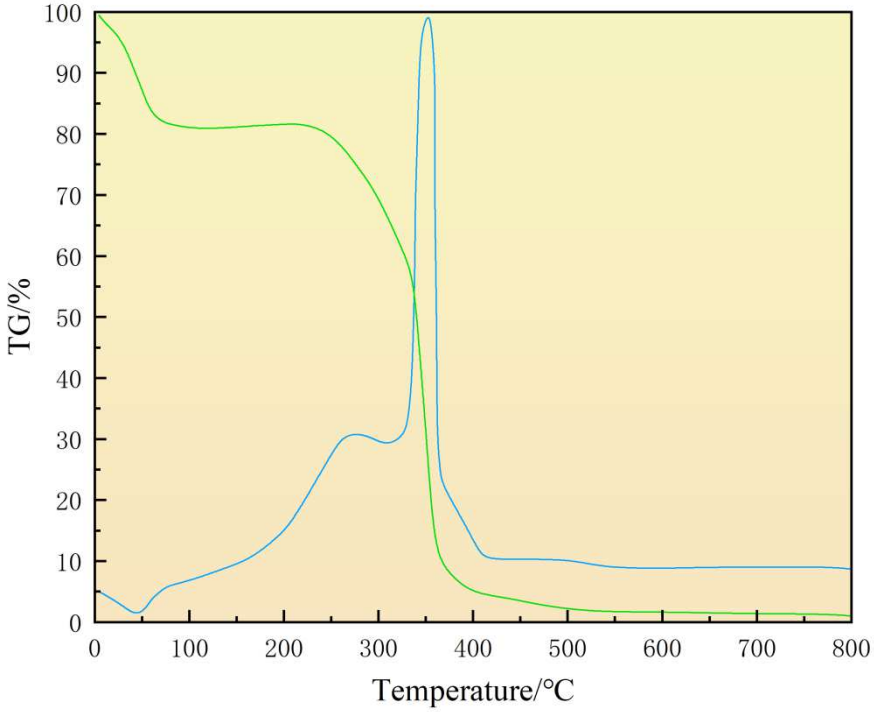


Figure 5 TG-DSC curve example[63]

Overall, these research findings provide vital references for further investigations on low-temperature oxidation kinetics of gas-bearing coal. A typical experimental technical route for coal spontaneous combustion is formed as follows: prepare standardized coal samples at first; then adopt gas chromatography, TG-DSC and other instruments to acquire multi-dimensional raw data; subsequently calculate core kinetic parameters via kinetic analytical methods, systematically revealing the evolution rules of activation energy, pre-exponential factor and other key parameters varying with gas concentration, coal rank, pre-oxidation temperature, moisture content and external thermal effects; and finally summarize the macroscopic characteristics and intrinsic mechanisms of coal spontaneous combustion under diverse working conditions (as shown in Figure 6).

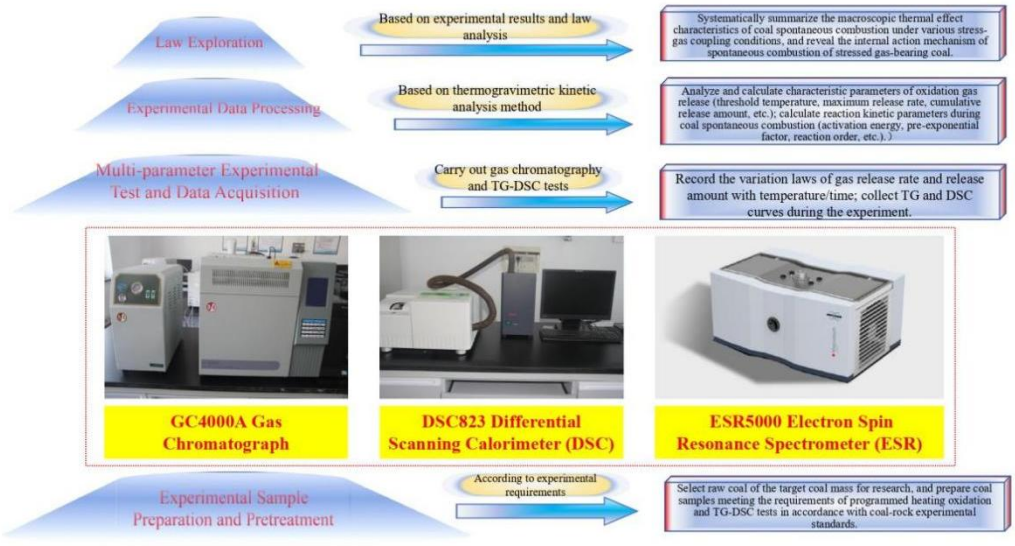


Figure 6 Technical Route for Research on Coal Oxidation Kinetics

2 Microstructural Evolution Characteristics of Stressed Gas-Bearing Coal During Temperature Rise

Microscopically, low-temperature oxidation of coal also exhibits distinct staged features. Varying stages differ greatly in gas competitive adsorption, gas desorption-seepage capacity and micro-functional groups, which serve as vital basis for exploring internal spontaneous combustion mechanisms. Previous sections have reviewed existing experimental apparatuses developed by scholars. Tests carried out on such equipment reveal prominent disparities in functional groups and microstructures of coal samples before and after oxidation, which further clarifies the intrinsic microscopic oxidation mechanism of stressed gas-bearing coal under heating.

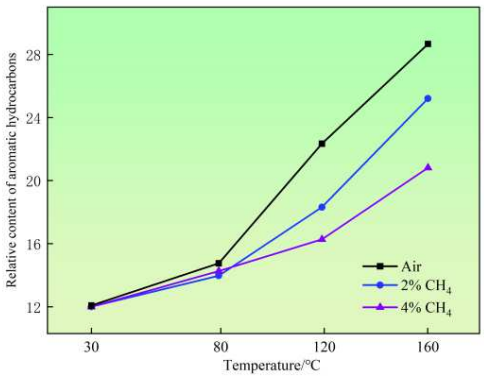
2.1 Functional Groups

Chemically, coal is a complex mixture consisting of diverse high-molecular organic compounds. Coal undergoes a series of physicochemical changes including chemical bond breakage and functional group transformation during coal-forming, metamorphism and mining-induced unloading, generating abundant oxygen-reactive active sites on coal surfaces and endowing coal with high oxidation activity and spontaneous combustion liability. Macroscopic generation of indicator gases such as CO and CO_2 is the external manifestation of such microscopic chemical transformations. Coal low-temperature oxidation proceeds through three phases: slow low-temperature reaction, self-accelerated heating and rapid combustion. Once temperature exceeds critical thresholds, oxidation reactions undergo abrupt staged transitions. Microscopic evolution of functional groups and dynamic variation of free radicals can precisely reflect such staged shifts, providing key microscopic evidence for revealing coal low-temperature oxidation mechanisms.

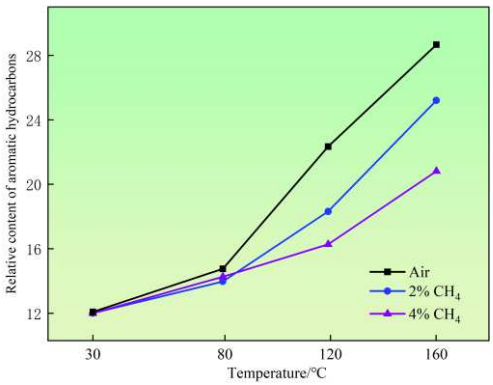
Hao Yu et al.[27,54] conducted experiments under variable methane atmospheres and found that methane competes with oxygen for adsorption sites, reducing effective oxygen supply, restraining oxidative decomposition of active functional groups, elevating apparent activation energy, and lowering oxidation rate, gas and heat output, thereby remarkably delaying low-temperature spontaneous combustion. Lü Zhiguang and Xu Yongliang et al.[31-33] revealed regular evolution of oxygen-containing groups, aliphatic hydrocarbons and aromatic structures during long-flame coal oxidation, with 120°C as the critical temperature. Carboxyl content rises continuously with temperature; C–O bonds of phenols, alcohols, ethers and esters first increase then peak at 120°C before declining; hydroxyl groups are rapidly consumed after 120°C with sharply reduced concentrations. Methyl and methylene groups in aliphatic hydrocarbons rise first and fall, reaching maximum reactivity at 120°C. Aromatic structures remain generally stable with slight initial decline followed by growth, and their consumption accelerates drastically at high temperatures. Methane participates in competitive adsorption during heating and alters coal spontaneous combustion properties. Wang Fei, Liu Jing et al.[29-30] tested coal samples treated under different methane concentrations and proved methane molecules preferentially occupy internal pores and surface active sites to form competitive adsorption, blocking oxygen adsorption and diffusion, inhibiting oxidation of aliphatic chains and oxygen-containing groups in weakly caking coal,

raising apparent activation energy and reducing heat and gas generation to slow low-temperature oxidation significantly.

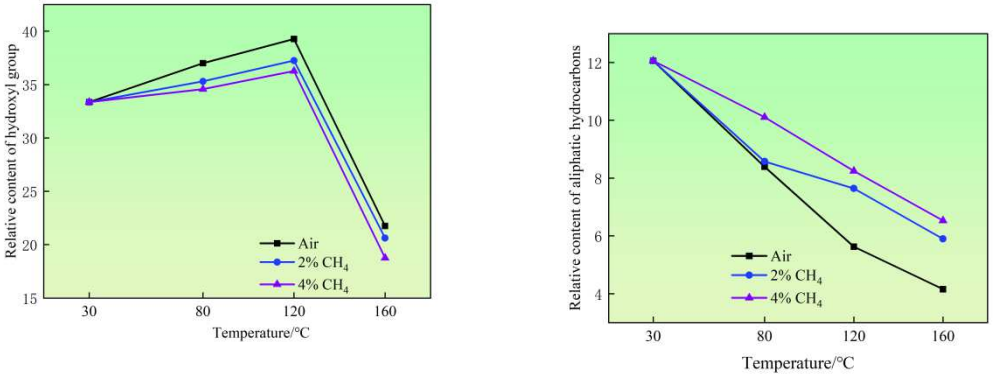
Apart from the above research, numerous scholars have investigated functional group evolution of various coal types during oxidation. Deng Jun et al. adopted FTIR and microcalorimetry to analyze coal low-temperature chemical properties. Results show aliphatic hydrocarbons are continuously consumed, hydroxyl groups rise then drop[65], while oxygen-containing and aromatic hydrocarbons accumulate as oxidation proceeds. Methane occupies adsorption sites to suppress group reactions, minimizing the growth of oxygen functional groups and consumption of aliphatics and delaying oxidation; the relative variation of functional groups is illustrated in the corresponding figure 7. Liu et al. stated that cleavage of oxygen-containing functional groups and aliphatic side chains constitute the microscopic core of CO and C_2H_4 generation in goaf coal fires[66]. Their reaction rates are controlled by temperature and oxygen supply, presenting delayed reactions and lower gas concentrations under open air leakage conditions. Zhao Jingyu et al. centered on functional group evolution and classified weathered coal oxidation into two stages: low-temperature oxidation (<200ºC) dominated by hydroxyl groups and medium-high temperature oxidation (200–400ºC) governed by aliphatic hydrocarbons[39]. Hydroxyl groups dominate early-stage reactions while aliphatic hydrocarbons control later oxidation. Existing research confirms aliphatic hydrocarbons are persistently consumed, hydroxyl groups rise and then fall, and oxygen-containing/aromatic groups keep accumulating during low-temperature oxidation. Methane hinders group reactions and delays oxidation, with stronger inhibition at higher concentrations. The figure intuitively displays the staged variation of microscopic functional groups throughout heating oxidation.



a aromatic hydrocarbon



b oxygen-containing functional group



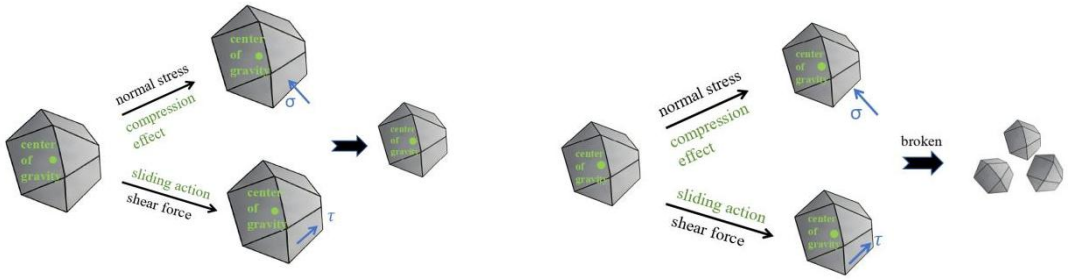
c hydroxyl

d aliphatic hydrocarbon

Figure 7 Variation Characteristics of Relative Content of Functional Groups During Temperature Rise[65]

2.2 Free Radicals

Free radicals act as core active sites in the chain reactions of coal spontaneous combustion. Their generation, transfer and evolution directly determine the low-temperature oxidation activity and spontaneous combustion liability of coal. Mechanical loading on coal not only damages its physical structure and alters particle gradation, but also triggers transformations of functional groups and free radicals within coal macromolecular frameworks[67-68]. In oxygen-bearing environments, enlarged specific surface area facilitates coal-oxygen reactions. Fractured gas-bearing coal produces abundant free radicals during fragmentation, which creates favorable conditions for spontaneous combustion and greatly raises the occurrence probability and overall risk of coal fire disasters.



(a) Mechanical compaction stage 1: Gradation change

（b）Mechanical compaction stage 2: Crushing occurs

Figure 8 Mechanical Compaction Process[67-68]

Domestic and foreign scholars have conducted extensive research on the generation mechanisms and evolution laws of free radicals in coal under various working conditions. Experiments by Ma Junrong et al. verified that thermal oxidation breaks and decomposes coal macromolecular structures under high-temperature oxidative environments[24], releasing volatile components and generating highly combustible free radicals such as CO, H_2 and C_2H_4. These active radicals can serve as ignition sources for gas, drastically reducing gas ignition energy and

triggering gas combustion and explosions. Zhai Xiaowei et al. stated that stress loading induces mechanical fragmentation and internal structural damage of coal; massive covalent bonds in coal molecular frameworks fracture under external force to produce numerous unstable radical fragments[8], leading to a sharp surge in internal free radical concentration. Ren Wanxing et al. found that the generation and reaction intensity of free radicals evolve in stages during coal low-temperature oxidation: radical production is faint at low temperatures[34], massive aliphatic chain cleavage triggers radical explosion at medium temperatures, and highly active radicals form via macromolecular pyrolysis at high temperatures. Their variation is highly coupled with indicator gas emission and conforms to the three-stage Logistic model. Xu Huicong et al. illustrated that multi-field coupling of stress, temperature and dynamic disturbance compresses coal macromolecules and fractures abundant internal covalent bonds, sharply raising radical concentration and greatly increasing active sites available for coal-oxygen reactions[35]. Microstructural damage and cracks induced by multi-field coupling further facilitate radical generation and transfer, accelerating chain reactions and significantly enhancing coal's low-temperature oxidation activity and spontaneous combustion liability. Starting from thermo-mechanical coupling, Chao et al. pointed out that thermo-mechanical interaction fractures coal covalent bonds to boost radical concentration and chemical activity[28], regulating activation energy to decrease with rising temperature and drop first then rise with increasing stress. Radical yield peaks and activation energy hits the medium-stress minimum, corresponding to the worst coal thermal stability and highest spontaneous combustion risk.

In addition, Hu et al. adopted molecular dynamics and DFT quantitative calculation methods to quantitatively characterize the global reactivity[69], Fukui indices and bond energies of various functional groups and bridge bonds in coal. The results revealed that sulfur atoms in -SH and -S-S- act as the most active sites for coal spontaneous combustion, and all bridge bonds tend to fracture at low temperatures. This finding elucidates the internal combustion-promoting mechanism of sulfur-containing structures at the molecular scale and provides theoretical support for the quantitative analysis of the microscopic mechanism of coal spontaneous combustion. Zhu Lingqi et al. selected four coal types (lignite, long-flame coal, gas coal and fat coal) and adopted EPR and programmed oxidation tests to explore the correlation between radical concentration and CO output during low-temperature oxidation[51]. The experimental results are shown in Figure 9. The radical concentration and CO production evolve synchronously with oxidation, featuring slow growth followed by accelerated increase starting at approximately 90ºC, as illustrated in the corresponding figure. Ji Yucheng et al. combined ESR and FTIR tests and found that lignite free radicals accumulate in a slow-fast-slow three-stage pattern with temperature[70]; radical types first decrease then multiply, and hydroxyl radicals act as core active intermediates to upgrade chain reaction pathways. Their dynamic evolution is tightly coupled with functional group cleavage and reaction transformation, jointly dominating the self-accelerating process of coal low-temperature oxidation. Using electron spin resonance spectroscopy, Hu Shibo investigated the microscopic evolution of stressed gas-bearing coal[71]. The results show that internal radical concentration declines with rising pre-adsorption gas pressure yet grows continuously as oxidation temperature rises, revealing the intrinsic chemical mechanism of coal thermal oxidation. Coal radical concentrations exhibit a staged pattern of mild variation followed by rapid growth under all conditions. Such evolution laws can directly reflect differences in low-temperature oxidation

progress and lay an important theoretical foundation for subsequent research on dynamic radical evolution under multi-field coupling.

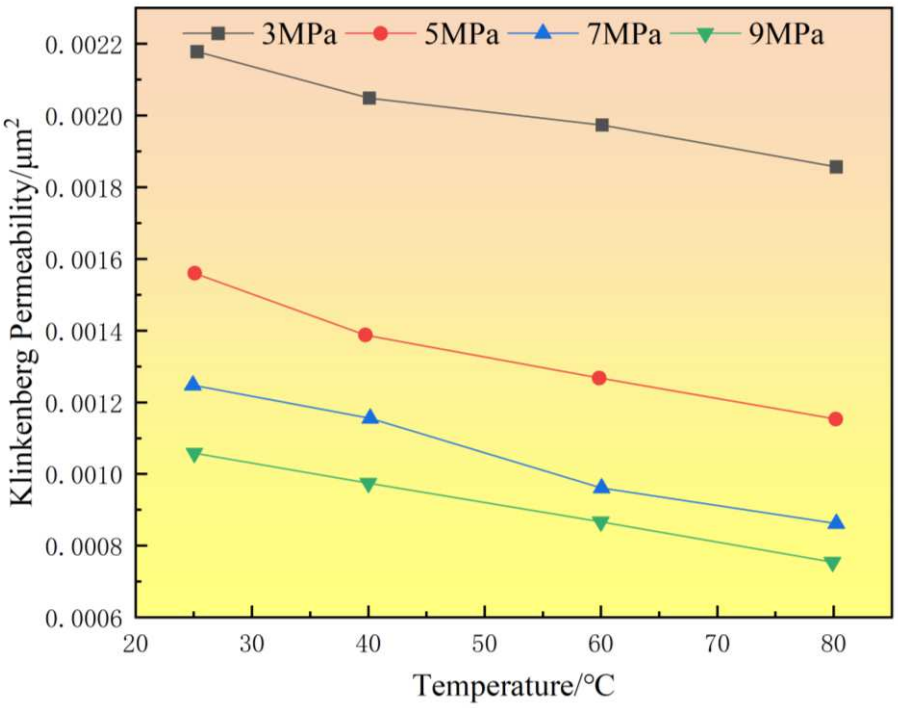


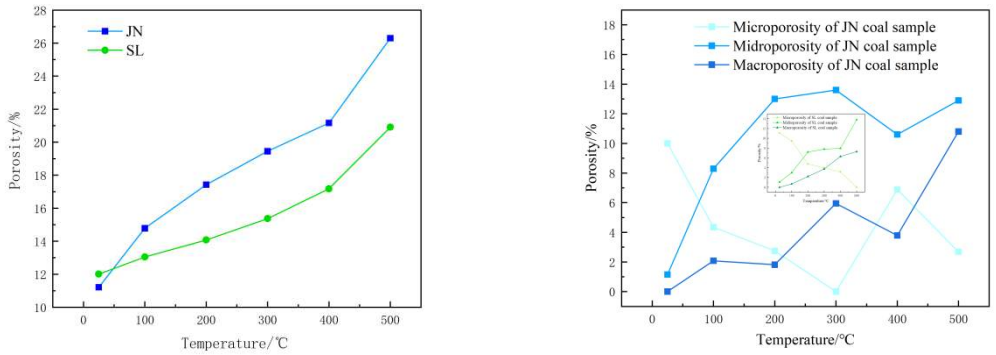
Figure 9 Free radical variation curve during the temperature rise process of each coal sample[51]

2.3 Pore Structure

From the perspective of microscopic physical structure, methane exerts certain impacts on coal pores during heating oxidation, while coal micro-pores serve as core channels for gas adsorption, desorption and seepage. Accordingly, the intricate micro-pore structure of coal must be analyzed when investigating spontaneous combustion disasters of gas-bearing coal. Scholars generally study pore characteristics via porosity and permeability: the former reflects static structural features, and the latter represents dynamic transport performance. Porosity and permeability are fundamental parameters governing the low-temperature spontaneous combustion of gas-bearing coal. At low temperatures, free gas occupies seepage channels and adsorbed methane generates competitive adsorption, jointly restraining coal-oxygen reactions. As oxidation temperature rises, the evolution of pore structure and gas desorption alter permeability and oxygen concentration, dynamically regulating the combustion process.

Regarding the variation of porosity — the core parameter of coal pores — during low-temperature oxidation, most scholars confirm a three-stage trend: slow initial growth, accelerated increase in the medium oxidation stage, and decline in the late oxidation stage. Lin Haifei et al. conducted full-process simulation experiments of gas adsorption-desorption-seepage under stress loading[72]. The results show that thermal expansion dominates coal at the early oxidation stage with fast porosity growth; as temperature rises, coal matrix plasticity enhances and the coal shrinks inward under stress, reducing porosity and slowing oxidation reactions. Liu Wei et al. proposed that pores slightly expand at the initial low-temperature stage with mild porosity growth; numerous meso- and macropores form in the accelerated medium-temperature stage[73],

sharply lifting porosity, while pore collapse occurs at high temperatures leading to an abrupt drop in porosity. Taking temperature and stress as experimental variables, Ma et al. found variable load and temperature jointly control coal pore evolution[11]. Axial load causes effective desorption area to decrease first then rise; confining pressure inhibits pore development whereas temperature promotes fracture expansion. Pores and desorption channels are most developed in the residual deformation stage. Li Jinglei's research has concluded that the pore evolution law of coal samples exhibits consistency[74], with total porosity continuously increasing as temperature rises (as shown in Figure 10). Due to the effects of heating and chemical reactions, coal pores undergo three stages in sequence: micropore reduction, rapid development of mesopores and macropores, and pore and fracture connectivity and expansion. The temperature range of 200~400ºC is an active interval for pore structure development, while micropores are the main pore type in the low-temperature stage. As temperature increases, micropores gradually expand into mesopores and macropores.



(a)Variation curve of total porosity of experimental coal samples

(b)Variation curve of micporosity, midporosity and maxporosity

Figure 10 Example of Porosity Variation[74]

Permeability serves as the macroscopic external manifestation of dynamic micro-pore evolution, and its variation essentially comprehensively reflects microscopic pore characteristics including connectivity and pore size. Conversely, macroscopic permeability changes exert feedback effects on gas migration and oxygen supply inside micro-pores, thereby governing the progress of coal spontaneous combustion. Domestic and foreign scholars have conducted extensive research on the coupled evolution mechanism of permeability and micro-pore structures under stress, temperature and multi-field coupling conditions, and core findings unanimously confirm that micro-pore structures exert decisive regulatory impacts on coal spontaneous combustion. Specific research achievements are summarized as follows: Pan Rongkun et al.investigated spontaneous combustion characteristics of coal after unloading under various initial stresses and found that pore structure and permeability of unloaded coal evolve distinctly in stages with initial stress[25-26] . Coal samples subjected to different initial stresses possess vastly diverse microstructures; total pore volume, micropore proportion and permeability all rise first and then peak at the critical stress of 25 MPa, where fractures are fully interconnected to deliver optimal seepage capacity. The evolution of microscopic functional groups is highly consistent with oxidation activity, revealing that stress exerts a prominent control effect on the spontaneous combustion performance of coal at the microscopic scale. Sun Rui et al. demonstrated that rising effective stress compresses coal pores to reduce permeability[75], while elevated temperature

narrows pore apertures via thermal expansion and also lowers permeability. Under coupled thermo-mechanical conditions, coal deformation and permeability variation show strong coupling behavior, and permeability is more sensitive to effective stress than temperature. Yang Kai et al. performed triaxial seepage tests and verified that coal permeability declines exponentially with growing confining pressure and decreases nonlinearly with rising temperature[76]. Under temperature-confining pressure coupling, high temperature intensifies pore compression caused by high confining pressure, leading to a far larger permeability reduction than single-factor conditions, which indicates an obvious synergistic inhibitory effect and further verifies the synchronized staged variation of permeability with temperature(as shown in Figure 6). Zhang Tianjun et al.carried out seepage experiments with cyclic pore pressure and cyclic confining pressure on fractured coal of different particle gradations[77]. The results show cyclic loads reconstruct pore structures and reduce tortuosity to improve permeability, with lower-graded coal exhibiting more remarkable permeability growth; cyclic pore pressure imposes a stronger influence than cyclic confining pressure. By utilizing a self-designed negative-pressure drainage experimental system, Zhang Hongzhen found that negative pressure significantly modulates the seepage performance of fractured coal by altering pore architecture and fluid flow patterns[78]. The negative pressure sensitivity coefficient of permeability generally decreases as negative pressure increases, and permeability is more responsive to pressure fluctuations under low negative pressure (60kPa).

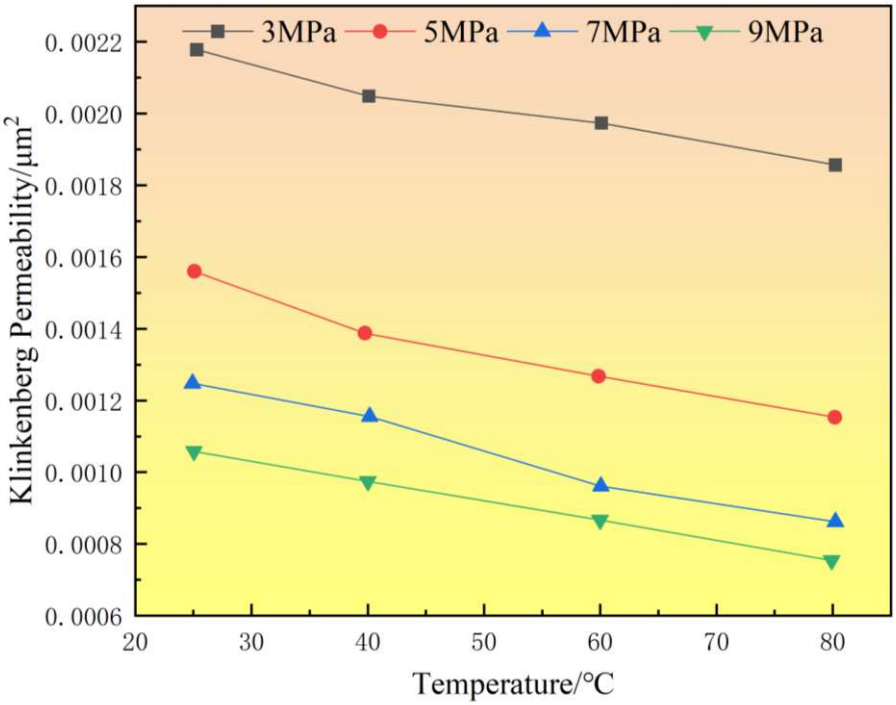


Figure 11 Permeability Variation Curves of Test Coal Samples with Temperature[76]

In summary, the microscopic pore structure of coal acts as the core regulatory medium governing the low-temperature spontaneous combustion process of gas-bearing coal. Its evolution reflects the microscopic action and influence mechanisms of macroscopic factors such as stress and temperature. Variations in pore quantity, size, connectivity and other microscopic properties under these macroscopic factors drive the evolution of porosity and permeability. As a concentrated representation of static pore distribution characteristics, porosity directly determines gas storage capacity within coal and the contact area for coal-oxygen reactions. Permeability, the

macroscopic external manifestation of dynamic pore evolution, directly governs the supply efficiency of internal oxygen and the smoothness of gas migration. The coordinated variation of porosity and permeability further directly affects the rate and intensity of coal-oxygen composite reactions, thereby regulating the initiation, development and evolution of coal spontaneous combustion. All factors interact and interrelate, forming a coupled restrictive relationship among macroscopic external factors, microscopic pore structural evolution and coal spontaneous combustion processes, as shown in Figure 8. Existing studies have revealed the interaction laws between macroscopic factors and microscopic pore structures, clarified the dominant influence of pore structures on the spontaneous combustion of gas-bearing coal, and provided crucial support for an in-depth elaboration of the seepage-reaction coupling mechanism of gas-bearing coal spontaneous combustion.

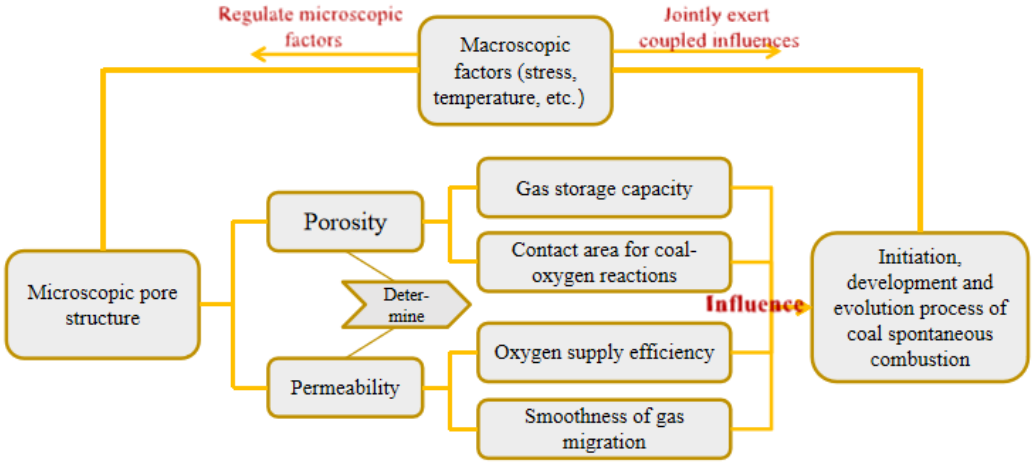


Figure 12 Coupling Restriction Relationship Between Coal Microscopic Pore Structure and Macro Factors of Coal Spontaneous Combustion

3 Discussion and Outlook

As stated above, the heating oxidation process of fractured gas-bearing coal under stress exhibits distinct staged macroscopic characteristics. Macroscopic phenomena correspond to microscopic variations, and microscopic structural changes in turn alter macroscopic reaction behaviors. The mutual verification between macro and micro perspectives provides solid theoretical support for interpreting coal spontaneous combustion mechanisms and reliable scientific guidance for mine fire early warning and prevention.

3.1 Spontaneous Combustion Characteristics of Fractured Gas-Bearing Coal Under Stress

Low-temperature spontaneous combustion of fractured gas-bearing coal under stress is a complex multi-field coupling process controlled by stress, gas and temperature, with obvious staged macroscopic evolution. At the low-temperature stage, competitive adsorption of methane dominates, accompanied by slow oxygen consumption and weak gas emission. At the medium-temperature stage, coal-oxygen composite reactions are drastically accelerated, and oxygen consumption rate and indicator gas output rise nonlinearly. At the high-temperature stage, chain reactions trigger rapid heat release and sharp temperature rise, leading to a sharp surge in

fire risk. The whole evolution follows a typical three-stage pattern: slow oxidation, accelerated oxidation and rapid violent oxidation.

Future research should target complex in-situ multi-field coupling conditions and break the limitations of existing single-factor experiments. Self-developed integrated test platforms and improved experimental methods can be adopted to carry out systematic heating oxidation tests on fractured gas-bearing coal samples under various stress levels, pre-adsorbed gas pressures and particle gradations. Quantitative analysis can be conducted to clarify how key parameters such as loading stress and pre-adsorption gas pressure affect characteristic spontaneous combustion indices including gas generation rules, oxygen consumption rate and heat release performance. Quantitative mathematical correlations between oxygen consumption rate of gas-bearing coal and stress/temperature can be established via data fitting. Combined with coal oxidation kinetics theory, the evolution laws of kinetic parameters of gas-bearing coal under loading can be further explored, so as to ultimately reveal the staged evolution characteristics and transition mechanisms throughout the whole spontaneous combustion process of fractured gas-bearing coal under stress.

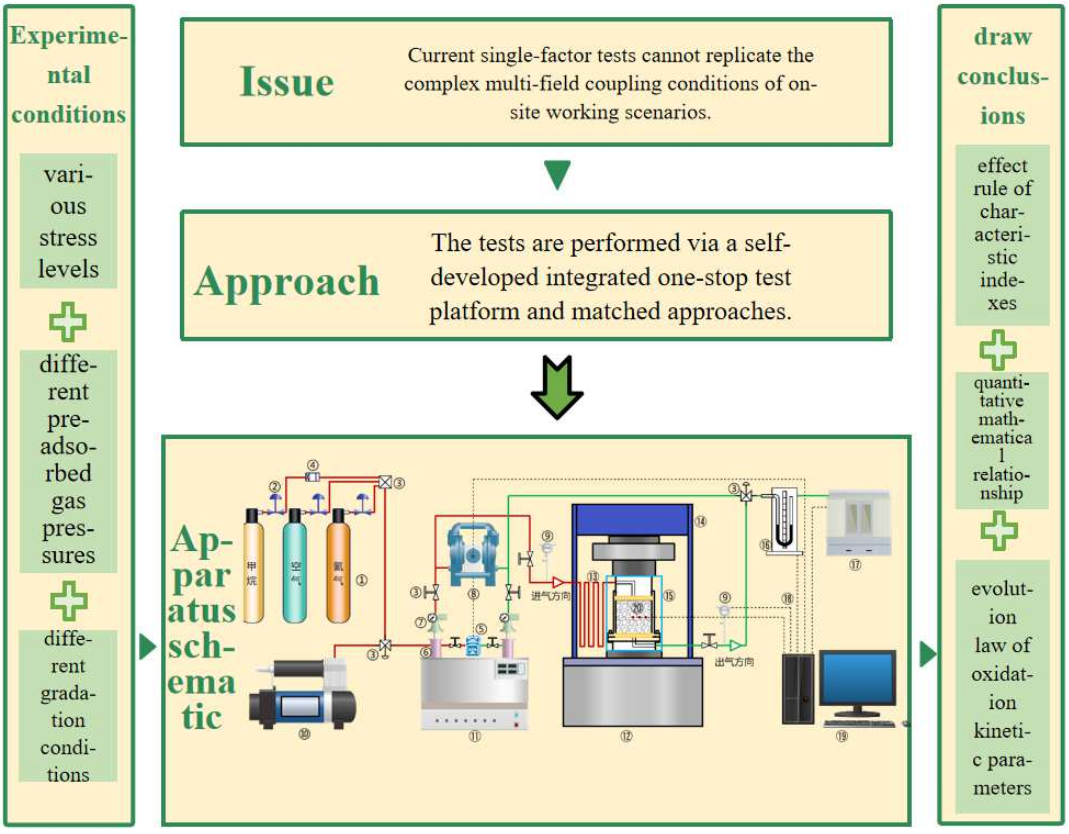


Figure 13 Technical Route Framework for Future Prospect of Spontaneous Combustion Characteristics of Stressed Fractured Gas-Bearing Coal

3.2 Microstructural Evolution Characteristics of Stressed Gas-Bearing Coal During Temperature Rise

Microscopically, oxidation is accompanied by staged evolution of free radicals and active functional groups. At low temperatures, physical adsorption and minor weak bond cleavage prevail, with faint radical generation and slow consumption of functional groups. At medium temperatures, massive decomposition of aliphatic side chains and oxygen-containing functional

groups occurs, radical concentration rises exponentially and reaction activity increases remarkably. At high temperatures, pyrolysis of macromolecular frameworks produces abundant highly active free radicals to initiate chain reactions, accompanied by a marked drop in activation energy, which pushes coal into the self-accelerating oxidation stage.

Future research shall comprehensively adopt multi-scale physicochemical characterization techniques to test functional groups, free radicals and pore structural properties of raw and oxidized coal samples. The correlations between pre-adsorbed gas pressure, loading stress, oxidation temperature and microscopic characteristic parameters need to be explored. Combined with macroscopic staged features, the intrinsic linkage between microstructural evolution and coal spontaneous combustion can be clarified. The findings will offer scientific basis for graded early warning and prevention technologies of fractured gas-bearing coal spontaneous combustion, as well as theoretical support and technical guidance for spontaneous combustion risk evaluation and control in goafs of deep mines with high in-situ stress and high gas content.

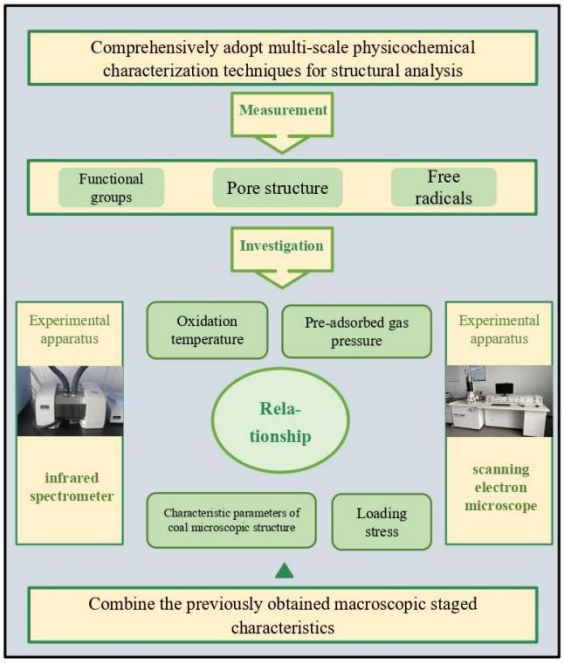


Figure 14 Technical Route Framework for Future Prospect of Microstructural Evolution Characteristics of Stressed Gas-Bearing Coal During Temperature Rise

3.3 Development Trend and Prospect of Engineering Application

Most existing studies adopt single-factor controlled experiments, which fail to sufficiently reveal the spontaneous combustion mechanism under multi-variable coupling conditions in actual underground goafs and thus cannot provide direct support for engineering applications. Therefore, future research shall target complex on-site multi-field coupling working conditions and break through the limitations of current single-factor experiments. Relying on the self-developed all-in-one tracing platform for stress-seepage-temperature rise oxidation coupling of fractured gas-bearing coal and adopting optimized experimental methods, integrated synchronous tests of stress loading, programmed heating and gas desorption-seepage can be realized in one station. Combined with the macroscopic and microscopic characteristic parameters obtained above, a multi-field coupling numerical model will be constructed and simulated to quantify the regulatory

laws of stress and adsorbed gas on the spatial-temporal distribution of each physical field. By comparing the results of physical simulation and numerical simulation, the disaster-causing mechanism of spontaneous combustion of stressed gas-bearing coal will be revealed from the multi-field coupling perspective, and the spatial-temporal evolution characteristics of dangerous areas as well as key triggering conditions of spontaneous combustion will be clarified. This series of research can fully reproduce the real multi-field coupling evolution process in underground goafs and remedy the defect that existing single-factor tests are inconsistent with field conditions. It quantifies the dynamic response laws of multi-field parameters, provides reliable theoretical and experimental support for spontaneous combustion risk prediction and zonal disaster prevention in goafs of deep high-gas mines, and possesses vital engineering value for restraining compound disasters induced by coal spontaneous combustion and gas and guaranteeing the safe mining of deep coal resources.

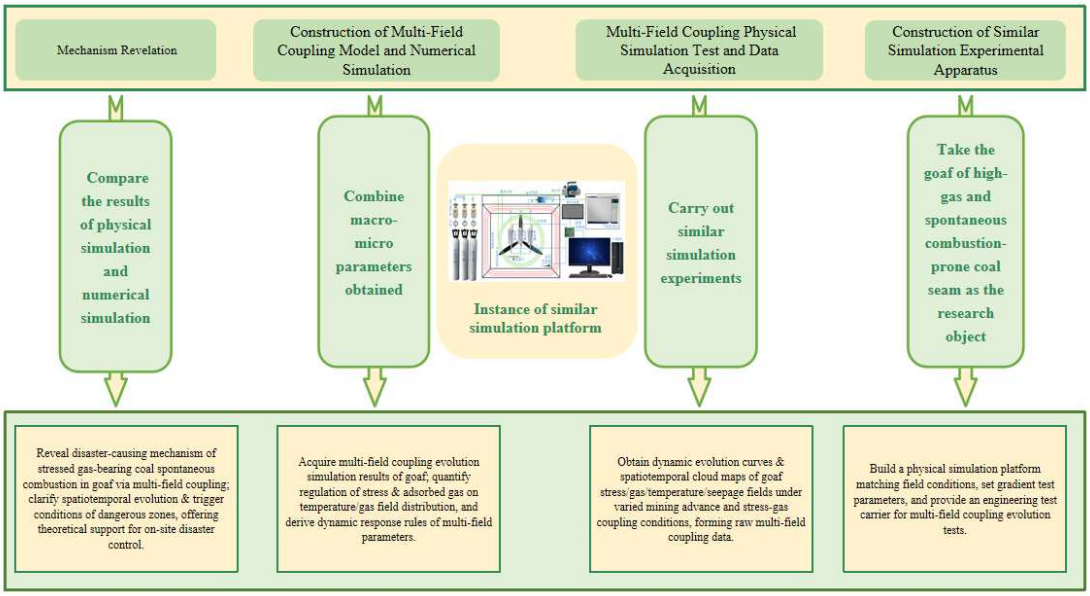


Figure 15 Technical Roadmap for Future Research Prospect

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Authors' contributions

Conceptualization, Tian Fuchao; Methodology, Tian Fuchao; Supervision, Tian Fuchao; Data curation, Du Rui, Wang Libin and Ding Wenbo; Funding acquisition, Tian Fuchao; Validation, Chen Mingyi, Lu Yi and Zhao Pengtao; Writing – original draft, Du Rui; Reviewing and editing – original draft, Tian Fuchao, Zhang Yu and Jia Kangteng. All authors have read and agreed to the published version of the manuscript.

Conflicts of interest:

The authors declare no conflicts of interest.

Declarations

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.

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