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Review

Research Status and Development Trend of Coal Spontaneous Combustion Fire and Prevention Technology in China: A Review

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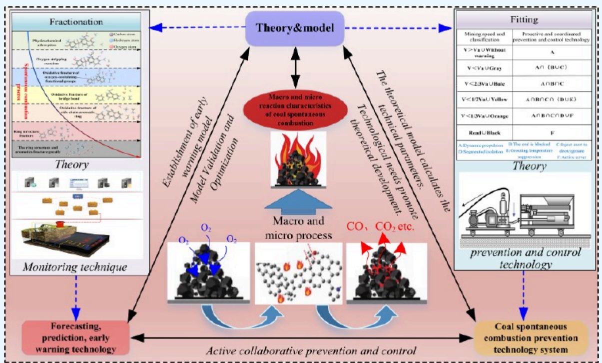

ABSTRACT: Coal seam spontaneous combustion fire is not only one of the main forms of the five major mine disasters, but also the main cause of secondary disasters such as mine gas and coal dust explosions. In recent years, with the advancement of mechanization, automation, and intelligent mine construction, spontaneous coal fires in mines have presented a series of new characteristics, and the prevention and control of spontaneous coal fires are also facing new challenges. On the basis of literature research, this paper summarizes and discusses the basic theory of coal spontaneous combustion, monitoring and early warning methods, and prevention and control technology, summarizes the development process of coal spontaneous combustion theory, reviews the research progress of coal spontaneous combustion monitoring and early warning methods and prevention and control technologies, and discusses the future development direction. In terms of the basic theory of spontaneous combustion of coal, from the initial hypothesis of spontaneous combustion of multielement coal to the unified understanding of coal-oxygen composite theory, a complete set of theoretical systems have been established, and a lot of macro and micro studies have been carried out and analyzed from multiple perspectives. In terms of coal spontaneous combustion monitoring and early warning, from the initial single indicator gas early warning to the construction of gas index system, the hierarchical early warning system is studied, and gradually tends to be perfect. With the development of automation and intelligence technology, the monitoring of coal spontaneous combustion disasters has also formed a new monitoring technology with beam tube monitoring as the traditional method, distributed optical fiber, wireless AD hoc network temperature measurement, and a coal spontaneous combustion multiparameter wireless monitoring system. In terms of fire prevention and control, the traditional "prevention" and "treatment" have changed to the "prevention−control−extinction" technical system based on hierarchical early warning, and the focus has gradually shifted to "prevention", and a large number of antifire materials have been developed, including blocking materials and fire-fighting materials. However, the precise inhibition and control of coal spontaneous combustion disasters, the evolution model of coal spontaneous combustion under the conditions of multifactor coupling in the field, the reliability and stability of intelligent monitoring system, the noncontact detection method of fire source, and the collaborative adaptation of multiple prevention and control techniques are not yet clear. In the future development, the mechanism of spontaneous coal combustion and its evolution process and other basic theories should be deeply studied. On the basis of the mechanism optimization early warning method of spontaneous coal combustion process, flame retardant and fire prevention materials should be targeted and developed. On the basis of the spatiotemporal evolution of spontaneous coal combustion, monitoring and monitoring system equipment with high speed, high precision, and high stability should be developed, which should accelerate the realization of accurate dynamic sensing and intelligent early warning of coal spontaneous combustion, and form an active hierarchical collaborative prevention and control system based on the trinity of "prevention−control−extinction" of coal spontaneous combustion. The conclusions and prospects of this paper can be used for reference in the future research direction, and have a certain role in promoting the exchange of research results of coal science and technology workers.

1. INTRODUCTION

Coal is still one of the most important primary fossil fuels in the world, playing an important energy role in power engineering, metallurgy, the chemical industry, and other fields.[1] Coal fire disasters, as one of the five major mine disasters, seriously affect the safety of mine production. Coal,

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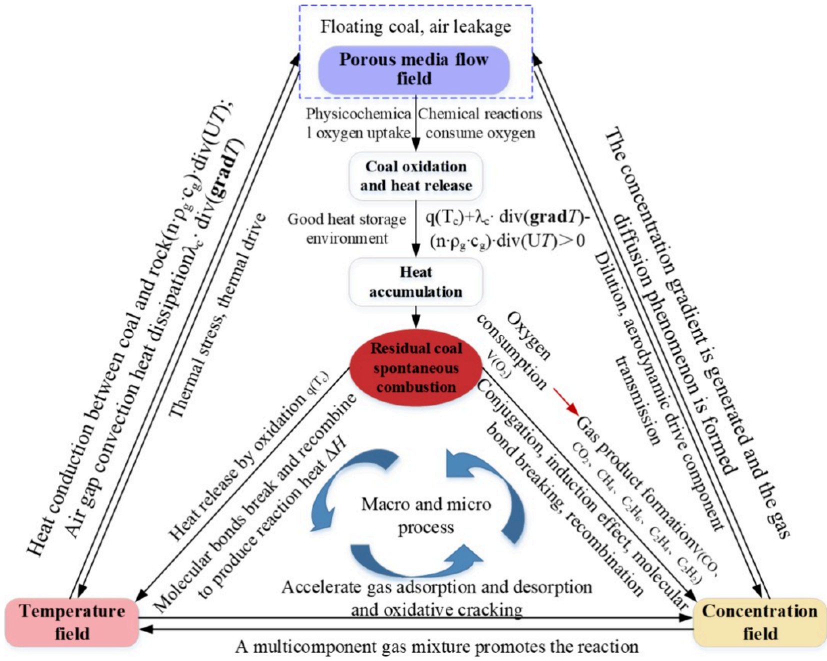

Figure 1. Oxidative spontaneous combustion mechanism and macroscopic and microscopic processes of floating coal.

with respect to the primary energy production and consumption structure, accounts for 68.8% and 57.7%, and for a long time into the future, coal will remian the dominant energy source in China.[2] At present, more than 90% of China's coal seam is classified as spontaneous combustion or easy spontaneous combustion, and the fire caused by coal spontaneous combustion accounts for 85% to 90% of the total number of mine fires. In addition, coal spontaneous combustion affects mines in Germany, the United States, India, Australia, South Africa, Poland, the Czech Republic, and other coal-producing regions and countries, representing a long-standing serious problem. In Germany, around ten coal fires per year are caused by spontaneous combustion in the Ruhr area. In India, CSC fires account for up to 75% of coalfield fire disasters, among which the Jharia coalfield fire is the most serious one.[3,4]

Whenever a spontaneous combustion disaster occurs in a mine, it not only results in the waste of a large amount of coal resources, but also easily leads to secondary disasters such as gas explosions and toxic gas diffusion, which seriously threaten the safety of underground mining personnel. During the "13th Five-Year Plan" period, China's coal fire disaster prevention and control technology has developed rapidly and diversified, and the prevention and control technology equipment and materials have been greatly enriched. In addition, the level of mechanization and intelligence of coal mines is also gradually advancing. In 2020, the degree of mechanization of coal mining and tunneling in China has reached 78.5% and 60.4%, respectively, and about 500 intelligent mining and excavation faces have been built.[4] However, with the shift of the focus of mining to the west, a series of new characteristics have emerged in coal spontaneous combustion fires, and mine fire prevention and control are also facing new challenges. For example, the development of coal resources is faced with problems such as complex geological conditions, increasing mining depth year by year, and multiple pressures of frequent coal fire disasters. It is difficult to accurately determine the location of high-temperature areas and spontaneous combustion environments in the goaf. Fire prevention and extinguishing work can easily require a lot of manpower, cause financial and material resources waste, and the actual effect is not good.[3] The essential reason lies in the precise inhibition and control of coal spontaneous combustion disasters, the evolution model of coal spontaneous combustion under the condition of multifactor coupling, the reliability and stability of the intelligent monitoring system, the noncontact detection method of the fire source, and the cooperative adaptation of multiple prevention and control techniques.

On this basis, through literature research, the authors have summarized the development process of the basic theory of coal spontaneous combustion, systematically sorted out and discussed the technical methods of coal fire disaster monitoring, forecasting, early warning and prevention technology and equipment, and put forward the relevant problems in disaster prevention and control and the future development direction. In order to provide a reference for the future research of coal spontaneous combustion and mine fire prevention technology.

2. RESEARCH PROGRESS OF BASIC THEORY OF SPONTANEOUS COMBUSTION OF COAL

Since the 17th century, people have explored the cause and process of coal spontaneous combustion, and put forward various hypotheses and theories, among which the main theories are the pyrite causing theory, bacterial causing theory, phenol hydroxyl causing theory, and coal sample compound causing theory. With the deepening of the research, the theory of coal-oxygen recombination was finally accepted and recognized, and a large number of related studies were carried out.

2.1. Mechanism of Spontaneous Combustion of Coal and the Macroscopic and Microscopic Reaction Process. At present, scholars at home and abroad generally believe that floating coal accumulation has porous characteristics and can be approximated as a porous medium flow field under the action of air leakage. Physical and chemical adsorption occurs between coal and oxygen in the air, and chemical reaction occurs when the temperature is high, and heat is released in this process. When the heat storage environment is good, heat accumulation leads to oxidation and spontaneous combustion of residual coal. In view of the natural oxidation process of coal, scholars have studied it from two aspects: micro characteristics and macro performance. The mechanisms of spontaneous combustion of floating coal oxidation and macro and micro processes are shown in (Figure 1). In the microscopic aspect, it is considered that coal is a complex compound composed of organic and inorganic substances, and there are some active structures in its surface molecules. In the process of compounding with oxygen, the active groups are subjected to conjugation and induction effects to physically and chemically absorb oxygen atoms, resulting in the fracture of coal molecular bonds, the recombination between molecules and atoms, and the reaction heat. However, due to the complexity of coal molecules, exploring the mechanism of coal spontaneous combustion through molecular structure has always been a hot topic and difficult problem in the world.

Since the beginning of the 20th century, scholars at home and abroad have made a series of explorations on the molecular structure of coal. In 1942, German scientist Fuchs constructed the molecular structure model of lignite for the first time. Since then, scholars have used different methods to build a series of coal molecular structure models, for example, Chermin and Krevelen's 1957 improved model of the Fuchs structure.[5] In 1960, the British scholar Given proposed the molecular structure model of bituminous coal by using infrared spectroscopy and X-ray diffraction and other experimental methods.[6] And, subsequently, the molecular structure model of bituminous coal was proposed by Wiser,[7] an American scientist, in 1975. One of the more famous is the Wiser model, shown in (Figure 2).

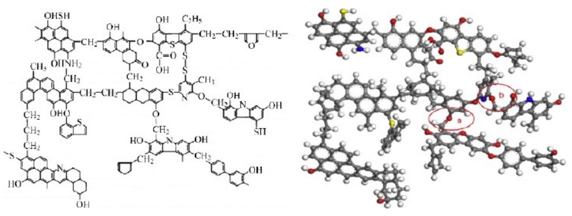

Figure 2. Molecule structure model of Wiser coal. Reprinted with permission from ref 8. Copyright 2018 Elsevier.

It is dominated by aromatic structures, and the aromatic rings are cross-linked by weak bonds such as ether bonds, thioether bonds, and short alkyl bonds, and sulfur atoms are built into the molecular structure model of coal for the first time.[9] It fully reveals the mechanism and law of producing sulfur-containing compounds in the combustion process of coal, which is recognized by most researchers. In 1988, Ge Lingmei, a Chinese scholar, analyzed the oxidation characteristics of active groups and explored the mechanism of spontaneous combustion of coal based on the Wiser molecular structure model;[10] Xu et al.[11] and Wen et al.[12] inferred 7 types of surface active structures based on physicochemical structures, analyzed the three-step reaction process of coal-oxygen recombination, explained the thermal effect of coal spontaneous combustion and the production mechanism of gas products, and initially revealed the microscopic mechanism of coal spontaneous combustion. Wang et al.[13] applied modern testing and quantum chemistry calculation methods to systematically discover 36 kinds of active sites and frontier tracks of active structural units in coal, and systematically mastered and obtained the active site structure and thermal dynamic parameters of each primitive.

Yu et al.[14] and Zhang et al.[15,16] studied the microscopic characteristics of the spontaneous combustion reaction of coal with different degrees of metamorphism through infrared spectrum testing, XRD, and elemental analysis, as shown in (Figure 3). It is found that the molecular structure of coal with

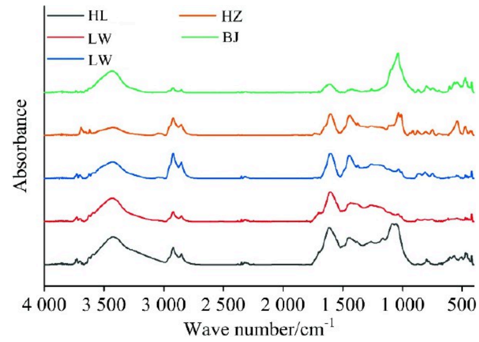

Figure 3. Infrared spectral characteristics of coals with same metamorphic degree. Reprinted with permission from ref 15. Copyright 2020 China Coal Research Institute.

smaller aromatic degree and ring condensation degree, shorter alkyl side chain length, and more bridge bonds makes the coal structure have stronger chemical activity and more easily oxidized. With the increase of coal metamorphism, the aromatic ring of coal molecules is deeply condensed, the structure content of fat layer is reduced, the crystal structure of microcrystals is gradually changed to graphite crystal structure, and the spontaneous combustion tendency and low temperature oxidation ability of coal are weakened.

Wang et al.[17] studied the molecular structure of coal and the microscopic reaction characteristics of spontaneous combustion by using infrared spectroscopy and quantum chemistry theory, and proposed the spontaneous combustion theory of coal microstructure and mass difference of component, believing that the quantity and quality difference of side chain groups and low molecular weight compounds is the essential index that determines the spontaneous combustion characteristics of coal. The substances that induce coal spontaneous combustion are the side chain groups of organic macromolecules and low molecular compounds in coal. The side chain groups of organic macromolecules containing noncarbon atoms in coal first adsorbed oxygen to release heat.

Zhang et al.[18] explored the application of ultrasonic extraction technology in the analysis of microscopic characteristics of coal oxidation, selected 7 extractants to extract functional groups in coal, and analyzed the extraction efficiency of different extractants on functional groups through infrared spectroscopy, electron paramagnetic resonance, and thermogravimetric analysis experiments. It was found that *N*-dimethylacetamide (DMAC) and *N*-methylpyrrolidone (NMP) had higher total extraction yield. DMAC and acetone can effectively extract aliphatic hydrocarbons from coal. Cyclohexanone (CYC) has the highest extraction rate for −C−O−C−, and NMP has the best extraction capacity for −OH. −OH is the main functional group that contributes the most to mass loss and heat release, as shown in (Figure 4).

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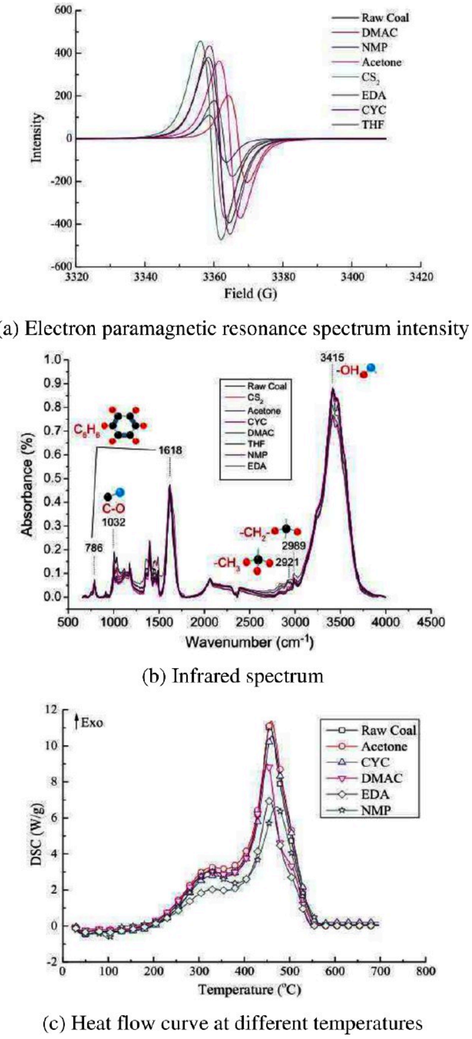

Figure 4. Variation characteristics of coal samples under the same extraction condition. Reprinted with permission from ref 18. Copyright 2019 Elsevier.

In the macroscopic aspect, a series of macroscopic phenomena occur in the process of coal spontaneous combustion, including the rise of coal temperature, the release of gas products, the generation of water, and the change in coal sample quality and activation energy. Since 1980, Chinese scholars have put forward a series of experimental testing methods and built a test platform to study the macroscopic law of coal natural oxidation process. A representative example is the large coal spontaneous ignition test bench of different scales (0.4, 0.8, 1, 1.5, and 15t coal loading capacity) built by Wen, Deng, and Liu et al., Xi'an University of Science and Technology[19−21] (Figure 5). The evolution characteristics of spontaneous combustion parameters such as gas product concentration, heat release intensity, and oxygen consumption rate were studied by simulating the spontaneous combustion process of floating coal under controlled environmental conditions. The comprehensive test system for spontaneous combustion characteristics of small coal (5−50g coal sample) developed by Wang et al.[22] of China University of Mining and Technology can achieve constant temperature, programmed temperature rise, and temperature tracking control at 20−400 °C. In addition, scholars have also established a temperature test system for high temperature procedures,[23] experimental system for spontaneous combustion of kilogram coal,[24] and a coal spontaneous combustion test system guided by equal temperature differences.[25]

At present, the research methods on the self-macroscopic performance of coal mainly focus on the spontaneous combustion and programmed temperature testing of the index gas and oxidation characteristic parameters in the process of spontaneous combustion of coal, the thermogravimetric (TG) test to analyze the change characteristics of coal mass during the oxidation process, and the thermal test (DSC, C80) to analyze the change law of coal heat emission and activation energy. With the continuous updating of experimental methods, domestic and foreign scholars have carried out systematic studies on the factors affecting coal spontaneous combustion, such as coal particle size,[26,27] water content condition,[28,29] and atmosphere condition.[30,31] In addition, Zhao et al.[32] studied the oxygen-poor oxidation characteristics of coal at high temperature and found that spontaneous combustion of coal can be maintained at 3% oxygen concentration under high temperature conditions. Wen et al.[33] and Deng et al.[34] studied the spontaneous combustion characteristics of secondary oxidation of coal and found that with the increase of coal metamorphism, the oxidizability of secondary oxidized coal samples was weakened. In the initial stage of secondary oxidation, the oxygen consumption rate and heat release intensity were greater than those of primary oxidation; in the later stage of reaction, the oxygen

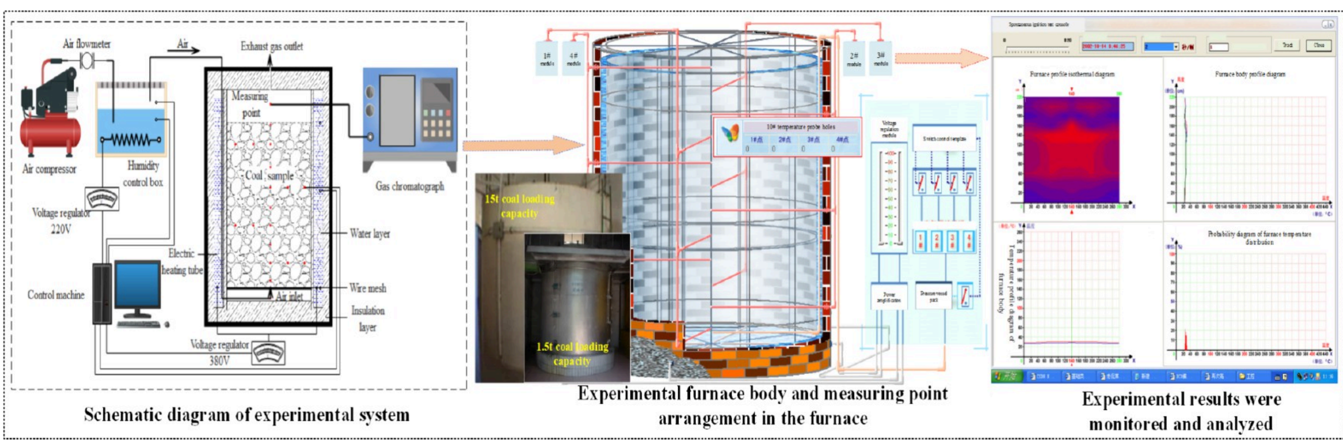

Figure 5. Large coal spontaneous combustion test bench.

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Table 1. Micromechanism of Formation of Coal Spontaneous Combustion Products

reaction product	microscopic mechanism	reaction mode
CO	The oxygen molecule attacks the carbon atom at the end of the propyl group on the side chain of the benzene ring, causing the propyl group to form an aldehyde group ($-CH_2-CH_2-CO-H$) and water, while the aldehyde group continues to decompose to form CO.	spontaneous reaction
CH_4	The oxygen molecule attacks the carbon atom in the middle of the propyl group on the benzene side chain, causing the propyl group on the benzene side chain to form acid groups ($-CH-COOH$) and CH_4.	spontaneous reaction
C_2H_4	Oxygen molecules attack the C(25) atom in the middle of the propylene group ($-(C25)H_2-C(26)H{=}C(27)H_2$) on the benzene side chain of the coal molecule, causing the propylene group on the benzene side chain to form an acid group ($-CH_2-COOH$) and ethylene.	spontaneous reaction
H_2O	Oxygen molecules attack the primary amine group on the benzene ring side chain $-C(29)H_2-N(22)H_2$. The N(22) atom in the middle of H_2, making the primary amine group on the benzene ring side chain of coal molecules to form the CH_2-NO group and water.	spontaneous reaction

consumption rate and heat release intensity were smaller than those of primary oxidation, and the characteristic temperature of spontaneous combustion was lower than that of primary oxidation. Zhang et al.[35,36] introduced the abrupt change theory to the spontaneous combustion process of coal and established a nonlinear dynamic model of the spontaneous combustion process combined with chemical reaction kinetics, which was verified by experimental methods. On this basis, the abrupt change temperature was proposed as an index to evaluate the tendency of spontaneous combustion of coal.

In addition, scholars often explain macro behavior through microscopic reaction rules. For example, Xu et al.[37] studied the change characteristics of active functional groups in the oxidation process through in situ Fourier infrared spectroscopy, and found that heat absorption by OH reaction was the main reason why heat was difficult to accumulate in the low temperature stage. When the OH reaction was exhausted, heat in coal accumulated rapidly and coal temperature rose rapidly. Deng et al.[38] studied the secondary oxidation spontaneous combustion process of coal with different degrees of metamorphism, and found that in the initial stage of the reaction, the C content of the secondary oxidized coal decreased, the specific surface area increased, and the pore volume increased, making the CO gas concentration greater than that of the primary oxidation. However, in the later stage of the reaction, due to the primary oxidation process, the CO gas concentration was higher than that of the primary oxidation.

The chemical reaction between coal molecules and oxygen consumes a large number of active functional groups such as hydroxyl, carbonyl, and ether bonds, so that the concentration of CO produced by secondary oxidation coal samples is lower than that of primary oxidation. Deng et al.[39] and Wang et al.[40,41] studied the reaction mechanism of CH_4 C_2H_4, H_2O, and CO generated by spontaneous combustion of coal by observing the infrared spectral characteristics of coal oxidation at different temperatures and combined with quantum chemical simulation. As shown in (Table 1). In summary, the macroscopic process of coal spontaneous combustion mainly includes heat accumulation, oxygen supply, temperature rise, and so on. The microscopic processes mainly include oxidation reaction, heat conduction, autocatalytic reaction, and so on. Among them, oxidation reaction, heat conduction, and the autocatalytic effect in the microscopic process directly affect the spontaneous combustion process of coal, while heat accumulation and oxygen supply in the macroscopic process indirectly affect these microscopic processes, and both promote the spontaneous combustion phenomenon of coal. In addition, the molecular structure of coal and the coal-oxygen complex chain reaction process in the microscopic aspect, as well as the characteristics of the "heat-gas-solid" reaction in the macroscopic aspect, these studies basically clarified the reaction process of the coal-oxygen complex, providing certain theoretical support for coal fire disaster prevention and control. However, limited by the complexity of coal molecular structure and the lack of existing research methods, the current research on the reaction process and mechanism of coal spontaneous combustion mainly focuses on the theoretical inference and quantum chemical simulation. The influence of different structures on the reaction of the coal molecular surface and its reaction mechanism are still the key problems that hinder the development of efficient prevention and control technology of coal fire disaster.

2.2. Construction of Mathematical Model of Spontaneous Combustion of Coal. Since the 1990s, Chinese scholars have conducted a lot of research on the mathematical model of coal spontaneous combustion oxidation heating process.[42] On the basis of theoretical analysis and experimental tests, a relatively complete theoretical system of coal spontaneous combustion has been proposed. Some of the key mathematical models are shown in (Table 2).

In order to grasp the strength of coal spontaneous combustion process and the degree of difficulty of coal spontaneous combustion, some scholars have established mathematical models of oxygen consumption rate, exothermic intensity, and gas product formation rate[46] on the basis of large-scale coal spontaneous combustion experiments. The determination index of coal spontaneous combustion tendency was established by the method of cross temperature point of degree heating test.[45] On this basis, the influence of particle size,[52] gas concentration,[53] water,[28] and other factors on the spontaneous combustion characteristics of coal with different metamorphic degrees were studied, which provided a lot of basic basis for the prevention and control of coal spontaneous combustion disasters.

On the basis of heat transfer, fluid mechanics theory and mathematical methods, a mathematical model of the necessary conditions for spontaneous combustion of coal in goaf is constructed.[43,44] On the basis of this model, the numerical calculation model of limit environmental parameters (lower limit oxygen concentration C_{min}, lower limit floating coal thickness h_{min}, upper limit air leakage intensity Q_{max}, etc.) for maintaining coal oxidation and spontaneous combustion is calculated.[44] These results provide an important theoretical basis for determining the dangerous area of coal spontaneous combustion in goaf and determining the technical means of coal spontaneous combustion prevention and control. Due to the complexity of the goaf environment, the parameters such as temperature and air leakage intensity are still difficult to measure directly and effectively. Combined with the

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Table 2. Key Mathematical Model of Coal Spontaneous Combustion Process and Its Application Scope

representation content	mathematical model	scope of application
necessary condition of coal spontaneous combustion[43,44]	$\underbrace{q(T_c)}_{q_1} + \underbrace{\lambda_c \mathrm{div}(\mathrm{grad}T)}_{q_2} - \underbrace{(n\rho_g c_g)\mathrm{div}(\overline{U}T)}_{q_3} \geq 0$	Judging whether the residual coal reaches the spontaneous combustion condition and calculating the limit parameters of coal spontaneous combustion are the basis for the division of coal spontaneous combustion danger zone.
coal spontaneous combustion tendency[45]	$I_{CO_2} = 100 \times \left(C_{O_2} - 15.5\right)/15.5$ $I_{T_{cpt}} = 100 \times \left(T_{cpt} - 140\right)/140$ $I = \phi\left(\phi_{CO_2} I_{CO_2} + \phi_{T_{cpt}} I_{T_{cpt}}\right) - 300$	The spontaneous combustion tendency of coal can be divided into three categories: easy spontaneous combustion, spontaneous combustion, and not easy spontaneous combustion.
oxidation characteristic parameters such as coal spontaneous combustion oxygen consumption rate, gas product formation rate, and heat release intensity[46]	$V_{O_{2,0}}\left(T, C_{O_{2,0}}\right) = QC_{O_{2,0}} \ln\left(C_{O_{2,in}}/C_{O_{2,out}}\right)/SL$ $V_{i,in}(T, C_{O_{2,in}}) = V_{O_{2,in}}(T, C_{O_{2,in}})C_{out}/\left[C_{O_{2,in}}\left(1 - e^{\frac{V_{O_{2,in}}\left(T, C_{O_{2,in}}\right)SL}{QC_{O_{2,in}}}}\right)\right]$ $\begin{cases} q_{max} = \frac{V_{CO,0}(T)}{V_{CO,0}\left(T\right)+V_{CO_{2},0}(T)} V_0(T)\Delta H_{CO} + \frac{V_{CO_2,0}(T)}{V_{CO,0}(T)+V_{CO_2,0}(T)} V_0(T)\Delta H_{CO_2} \\ q_{min} = \Delta H_r\left[V_0(T) - V_{CO,0}(T) - V_{CO_2,0}(T)\right] + \Delta H_{CO}V_{CO,0}(T) + \Delta H_{CO_2}V_{CO_2,0}(T) \end{cases}$	The basic parameters of coal oxidation characteristics can be used to evaluate the intensity of coal spontaneous combustion reaction, and to measure the kinetic parameters such as apparent activation energy and pre-exponential factor of coal body.
nonlinear oxygen consumption rate[47]	$V_{O_2}(T, C_{O_2}) = (C_{O_{2,in}}^{1-n} - C_{O_{2,out}}^{1-n})QC_{O_{2,0}}^{n}/[(1-n)SL]$	According to the sensitivity of coal spontaneous combustion rate to oxygen, the nonlinear consumption rate of coal to oxygen can be evaluated on the basis of determining the order of coal oxidation reaction.
spontaneous combustion period of coal[48]	$\Delta t_i = \sum_{i=1}^{n} \Delta t_i = \sum_{i=1}^{n} \frac{\left(C_{pi} + C_{pi+1}\right)\Delta T_i + 2\left(W_{pi}\lambda/100\right) + \mu_i Q' - \Delta qDi}{K_{qi}c_{qi}Q_s + K_{qi+1}c_{qi+1}Q_s}$	The theoretical calculation of the time required for coal oxidation from room temperature to different temperatures can measure the spontaneous combustion period.
coal spontaneous combustion oxidation zone in goaf[49,50]	$(C > C_{min}) \cap (h > h_{min}) \cap (\overline{Q} < \overline{Q}_{max})$	To determine the distribution range of "three zones" of coal spontaneous combustion in goaf and the dangerous area of spontaneous combustion.
air leakage intensity in goaf[21]	$\overline{Q}\left(x_i\right) = \frac{V_{O_2}^{0}\left(x_{i+1} - x_i\right)}{c_{O_2}^{0}\ln\left(c_{O_2}^{i}/c_{O_2}^{i+1}\right)^{s}}$	According to the distribution of oxygen concentration in goaf, the air leakage intensity in goaf is measured and the risk of spontaneous combustion of residual coal in goaf is evaluated.
prediction of CO emission in working face[51]	$V_{CO} = (\alpha Z_1 + \beta Z_2)LH(1 - \phi)\delta(T)/nQ^2$	Combined with the internal and external conditions of coal spontaneous combustion, the CO gas concentration in the upper corner of the working face under different mining conditions can be predicted.

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monitoring results of gas concentration in the goaf, the established coal oxidation "three zones" model can effectively judge the spontaneous combustion danger zone.[49,50] At the same time, the air leakage intensity calculation model established by the oxygen concentration distribution in the goaf has important reference value for the prevention and control of air leakage in the goaf. In addition, Zhai et al.[51] established a calculation model of CO gas concentration in the upper corner of the working face in combination with the internal and external factors of coal spontaneous combustion during the mining process of the working face, which revealed the upper corner CO. The reason for the accumulation of the iconic gas of coal spontaneous combustion provides a reference for the early warning of coal spontaneous combustion in the goaf.

The spontaneous combustion period of coal is a key parameter to prevent coal spontaneous combustion in goaf, and a more accurate value can be obtained through large-scale spontaneous combustion experiments.[54] However, due to the shortcomings of long experimental period, large test workload and poor repeatability, scholars have established a mathematical model of spontaneous combustion period from the perspective of oxygen absorption and heat release of coal, which provides a method for measuring the spontaneous combustion period of small coal quantity experimental results. Former Soviet scholar Kalenjin proposed to measure the oxygen absorption rate of coal by chromatography. Under adiabatic conditions, the time required for heating coal body and releasing water and gas in coal body when oxygen is absorbed by coal is recorded as the shortest natural ignition period of coal.[55] On the basis of the research of N.B. Kalienjin, Yu et al.[48] proposed a mathematical model for calculating the shortest spontaneous ignition period of a coal seam based on the chromatogenic oxygen absorption method, taking into account accelerated oxidation, intense oxidation, and oxidative heat release in the spontaneous combustion process of coal, and extended relevant parameters to the ignition temperature of coal to establish a mathematical model for the spontaneous ignition period of coal.

The above mathematical model provides an important theoretical basis for the prevention and control of coal spontaneous combustion disasters. A large number of scholars have embedded the model as a source term in commercial simulation software such as Fluent and COMSOL. Combined with the control equations of energy conservation, mass conservation, and momentum conservation embedded in the software, the numerical simulation of coal spontaneous combustion under different field conditions (goaf, coal pillar, coal pile, coal and gas coupling disaster, coalfield outcrop fire) is carried out. The evolution process of coal spontaneous combustion is reproduced from the perspectives of flow field, gas concentration field, and temperature field, which provides a basis for the prevention and control of coal fire disasters. For example, based on the mathematical model of coal oxidation reaction, Ma et al.[50] and Liu et al.[21] established a numerical simulation model of coal spontaneous combustion evolution under the condition of air leakage in multiple goafs. The air leakage law of small coal pillars was studied, and the distribution characteristics of "three zones" of coal spontaneous combustion in multiple goafs were explored. Zhang et al.[56] and Zhang et al.[57] established a numerical simulation model of coal spontaneous combustion based on the experimental results of coal oxidation kinetic parameters and numerical simulation methods. The variation law and moving path of temperature and gas concentration were studied, and the influence of water evaporation, coal pile height, coal type, wind speed, and bottom heat loss on the spontaneous combustion process of coal pile was obtained. Zheng et al.[58] and Xu et al.[59] established a coupling model of gas and coal spontaneous combustion in goaf, including coal oxidation, heat transfer, and gas desorption. The development and evolution of coal spontaneous combustion and gas disasters in static and dynamic goaf and their key influencing factors were studied, respectively. It is concluded that the gas accumulation area in goaf is directly related to the high temperature point and temperature of coal spontaneous combustion. Shi et al.[60] proposed to obtain reliable numerical simulation conditions through theoretical analysis, combined with the multiphysical field numerical simulation method to eliminate the influence of coal spontaneous combustion scale characteristics, studied the coal oxidation reaction intensity under closed conditions and nitrogen injection conditions, compared the coal spontaneous combustion reaction intensity, and obtained the "quasi-spherical" characteristics of coal slow oxidation and the "crescent" characteristics of rapid propagation.

The construction of key theoretical models fundamentally describes and characterizes the law of coal oxidation, which provides an important basis for the prevention and control of coal spontaneous combustion disasters. However, the frequent occurrence of coal fire disasters shows that these models still have certain limitations. The main reason is that the environmental characteristics of coal are very complex after mining, which is closely related to geological conditions, mining technology and other factors. Therefore, combined with the theory of mine pressure and the theory of coal spontaneous combustion, the development and evolution model of coal spontaneous combustion considering the coupling effects of air leakage and oxygen supply, coal crushing state, residual coal accumulation thickness and compaction degree, coal pore distribution, and other factors may be the content of further research in the future. The construction of these models will lay an important theoretical foundation for accurately grasping the law of spontaneous combustion, efficient detection of fire source location, and disaster warning.

3. RESEARCH PROGRESS OF COAL SPONTANEOUS COMBUSTION MONITORING, FORECASTING, PREDICTION, AND EARLY WARNING TECHNOLOGY

3.1. Coal Spontaneous Combustion Monitoring Technology.

3.1.1. Beam Tube Monitoring. Beam tube monitoring, as the most traditional monitoring means, is widely used in mines, goaf areas, shallow areas, and the inner area of roadway surrounding rock with different degrees of deformation. There are generally three monitoring methods: ①The beam tube is arranged at the monitoring point, and the gas is produced manually to the air bag and sent to the ground for chromatographic analysis. ②The beam tube arranged at the monitoring point is connected with the ground negative pressure pump and chromatographic analysis system to monitor the change of gas composition and concentration online. ③The chromatographic analysis system is arranged in the well, connected to the monitoring point by the beam tube, and connected to the ground-connected data acquisition system to realize online gas monitoring. The beam tube system

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can realize the continuous monitoring of the hidden danger of spontaneous combustion, and has the advantages of small size, simple use and maintenance, stable operation, high reliability, and easy failure,[61] but due to the long laying distance of the pipeline of the beam tube system, on the one hand, there is a delay in monitoring, and on the other hand, the system is difficult to maintain, and the phenomenon of blockage and gas leakage is easy to occur, which brings certain troubles to the field monitoring.

3.1.2. Wireless AD Hoc Network Temperature Measurement. Temperature is the most direct and accurate index to determine the degree of spontaneous combustion of coal. Since 2008, many enterprises and institutions such as Taiyuan Electronic Research and Design Institute and Xi'an University of Science and Technology have successively launched the research and development of wireless AD hoc sensor monitoring system for goaf temperature,[62,63] gradually opening up the field of wireless AD hoc network monitoring technology for coal spontaneous combustion temperature field in China.[64] Wireless AD hoc network temperature measurement is a temperature monitoring technology that collects temperature data through temperature sensor, transmits the signal to the gateway by wireless transmission, and then converts it into wired signal and transmits it to the ground analysis system. It changes the topology of the traditional temperature sensor system and adapts to more temperature measurement applications. Because the wired pipeline is completely abandoned, it is especially suitable for special environments such as the caving space in the gob. The hidden danger in the transmission process is small, but the signal transmission is unstable in complex underground conditions.

3.1.3. Distributed optical fiber temperature measurement. Optical fiber temperature sensor is a new temperature monitoring technology developed in the 1970s. Because it transmits information through optical signals, it has advantages such as real-time continuity, insulation, electromagnetic interference resistance, and high voltage resistance.[65] The distributed fiber optic sensor was first proposed by the University of Southampton in 1981.[66] The basic principle is that the reflected light in the fiber transmission undergoes Rayleigh scatter, Raman scatter, and Brillouin scatter,[67−70] and the intensity of the light wave is affected by temperature. By capturing the backscattered light waves, the temperature changes at each point in the cable can be demodulated, and the temperature can be continuously monitored in real time.[71−73] The system and principle are shown in (Figure 6).

In recent years, with the development of optical fiber technology, distributed optical fiber temperature measurement technology has been widely used in goaf temperature monitoring. It is suitable for high temperature, corrosive and other environments, antielectromagnetic interference, high sensitivity, lightweight, small size, low cost. However, the optical cable is easy to be damaged by aging and may have partial discharge problems.

3.1.4. Coal Spontaneous Combustion Multiparameter Wireless Monitoring System. Due to complex underground environmental conditions, hidden coal spontaneous ignition location, and poor thermal conductivity, it is difficult to accurately identify the risk degree of spontaneous combustion of coal in goaf with a single monitoring method. Scholars developed a wireless multiparameter monitoring system integrating temperature and humidity, gas and pressure difference sensors, as shown in (Figure 7), and applied it in several mines.[74,75] Through the integrated design of microelectronics, sensors, computer database, and other technologies, the system monitors important environmental parameters such as gas component concentration, temperature, and humidity, and pressure difference at the monitoring point in real time, and uses wireless communication technology to feed the information through the base station and the host to the computer data analysis system to realize the advance perception of coal fire disaster.

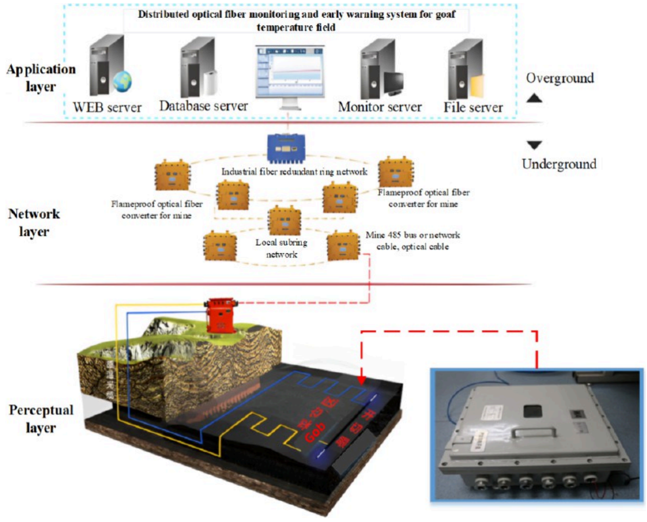

Figure 6. Distributed optical fiber temperature measuring system. Reprinted with permission from ref 72. Copyright 2013 Xi'an University of Science and Technology.

To sum up, the characteristics, application range, and advantages and disadvantages of the existing coal spontaneous combustion monitoring technology are shown in the following table (Table 3).

3.2. Coal Spontaneous Combustion Forecasting Technology. *3.2.1. Coal Spontaneous Combustion Tendency.* The spontaneous combustion tendency of coal refers to the inherent property of oxidation capacity of coal at normal temperature. Different countries in the world adopt different technical methods to realize the spontaneous combustion tendency test of coal. Some of these methods are XPT, gas indices studies, Russian U-index, Olpinski index, adiabatic calorimetry, self-heating temperature, Wits-CT index, peroxy complex analysis, DTA, Stage II Slope, WOP, modified XPT index, FCC, Wits-Ehac index, etc.[76−79] Results obtained from these experimental techniques have been used by researchers to categorize coal seams based on their liability toward spontaneous combustion. In the 1980s, Fushun Branch of China's Coal Science General Hospital proposed the identification method of coal spontaneous combustion tendency chromatographic oxygen absorption, with the oxygen absorption amount of coal at normal temperature and pressure as the main index to determine the ability to predict coal spontaneous combustion, the coal spontaneous combustion tendency grade is divided into three categories, namely: class I easy spontaneous combustion, class II spontaneous combustion, and class III not easy spontaneous combustion were adopted as national standards in 2006 (GB/T 20104−2006).[80] The test methods of coal spontaneous combustion tendency in various countries are shown in (Table 4).

3.2.2. Prediction of Coal Spontaneous Ignition Period. The spontaneous combustion period of coal seam refers to the

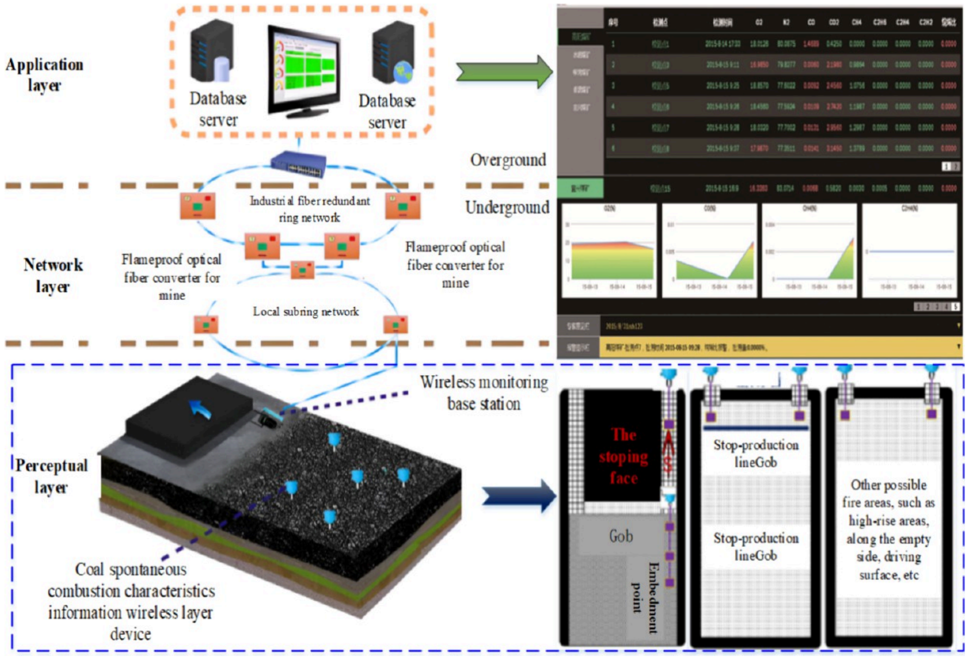

Figure 7. Wireless multi-parameter monitoring system for coal spontaneous combustion.

period of time from contact with air to spontaneous combustion of coal exposed during mining. Domestic and foreign scholars have carried out research on coal spontaneous ignition period by theoretical analysis, experimental testing, and other means. For example, Deng et al.[81] determined the experimental minimum spontaneous ignition period of coal under excellent experimental heat storage conditions by using a large coal spontaneous combustion physical similarity simulation test platform; Yu et al.[48] based on the research basis of 1984 Soviet scholar N. B. Kalenjin on coal spontaneous ignition period,[55] the mathematical model of the shortest time of spontaneous combustion of coal seam is constructed by using the hue oxygen absorption method, and the time required to heat up to a certain temperature is calculated. The spontaneous combustion period of coal is obtained by superposition method. Liang et al.[82] established the control equation for solving the shortest spontaneous combustion period of homogeneous and isotropic loose coal, and used the first integral method to solve the time required for coal to heat up to different temperature points, so as to determine the spontaneous combustion period of coal.

The spontaneous combustion time of abandoned coal can be roughly determined and the spontaneous combustion risk of abandoned coal can be basically determined through the experimental test or theoretical calculation during the spontaneous combustion period of coal. However, due to the idealization of experimental and theoretical research, the complex spontaneous combustion environment of abandoned coal in goaf, numerous influencing factors and the dynamic changing process of goaf in working face, there are often certain errors between the predicted results and the actual conditions.

3.2.3. Prediction of Coal Spontaneous Combustion Danger Area. The development of coal spontaneous combustion in goaf is an extremely complex dynamic process, which mainly depends on the characteristics of coal oxidation and heat release, oxygen supply conditions, and storage and heat dissipation environment. On the basis of the necessary conditions of spontaneous combustion of coal, Xu et al. determined the calculation method of the limit parameters of oxidative spontaneous combustion of floating coal. On this basis, they divided the "three zones" of spontaneous combustion of abandoned coal in goaf, and established the judgment conditions for the dangerous area of spontaneous combustion in goaf considering the advancing speed of working face, the thickness of floating coal, and the spontaneous combustion ignition period, namely:

$$(h > h_{min}) \cap (C_{O_2} > C_{min}) \cap (\bar{Q} < \bar{Q}_{max}) \quad (1)$$

lower limit oxygen concentration, %; Q_{max} indicates the upper limit By theoretical judgment, the "oxidation heating zone" is further divided into "oxidation heating zone" and "spontaneous combustion danger zone", as shown in (Figure 8), thus realizing the prediction of spontaneous combustion danger zone of coal in goaf.

Due to the difficulty in monitoring a wide range of environmental parameters in goaf, it is still difficult to master the whole spontaneous combustion danger area in goaf and determine the distribution characteristics of multiple fields through theoretical analysis. With the development of computational fluid dynamics (CFD) technology, scholars have carried out a lot of research on the spontaneous combustion risk of goaf based on the basic theory of coal oxidation kinetics and the judgment theory of spontaneous combustion danger area. For example, Huang et al.[83] studied the distribution characteristics of coal spontaneous combustion in three zones by constructing a goaf pore distribution model considering the caving of the old roof of the goaf, and verified it with the actual field results. Liu et al.[21] studied the risk of spontaneous combustion of coal in goaf of Goudao working face, and predicted the distribution characteristics of "three zones" of spontaneous combustion of coal in goaf of Goudao working face by using Fluent numerical simulation. In addition, Zhou et al.[84] used a Fluent dynamic grid model to conduct numerical simulation of the four-dimensional dynamic change

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of coal spontaneous combustion in goaf, taking into account the changes of time and space during the dynamic coal mining process, and studied the distribution characteristics of coal spontaneous combustion risk areas in goaf, as shown in (Figure 9).

Due to the unbalanced characteristic data of spontaneous combustion of coal in goaf and the large weight deviation of indicators, the method of deep fusion analysis of multisource data based on machine learning method to predict spontaneous combustion of coal has also been widely studied in recent years. For example, Shao et al.[85] and Zhao et al.[86] predicted the spontaneous combustion of goaf by establishing the PCA improved AdaBoost prediction model and the fusion and optimization of K-means, Relief, HSMOTE, SVM, and other algorithms. Lei et al.[87] and Deng et al.[88,89] introduced random forest method to predict the temperature of spontaneous combustion of coal in goaf, optimized the algorithm by particle swarm optimization, and compared the prediction results with support vector machine and neural network methods (Figure 10), finding that the machine learning algorithm was in good agreement with the actual monitoring results.

At the same time, based on the principle of coal spontaneous combustion prediction, relevant scholars have developed a variety of technical equipment suitable for coal spontaneous combustion early warning, including sensors and monitoring equipment for detecting temperature, humidity, gas concentration, and other parameters in coal mines or storage places; an intelligent monitoring system based on artificial intelligence, machine learning, and other technologies; fire prevention and control equipment for the rapid control of fire when the risk of spontaneous combustion occurs to prevent the spread of fire. Air purification and gas treatment equipment for the removal of hazardous gases from mines or storage sites; using big data analysis technology, combined with historical data and real-time monitoring data of coal mines or storage sites, prediction models, and software tools are developed, which can more accurately predict the risk of coal spontaneous combustion and provide corresponding suggestions for preventive measures. The development and application of these technical equipment can effectively improve the safety of coal mines and storage sites, reduce the occurrence of spontaneous combustion accidents, protect the safety of personnel and property, and promote the sustainable development of the coal industry.

3.3. Coal Spontaneous Combustion Prediction Technology. On the basis of the hypothesis of coal-oxygen recombination, a large number of scholars have conducted a lot of research on the development process of coal-induced fires in mines, and based on the early research results, the development process of coal-induced fires in mines is divided into three stages: incubation period, self-heating period, and combustion period by the critical temperature and ignition point temperature of spontaneous combustion of coal.[90] In the key areas of coal spontaneous combustion such as goaf, the variation characteristics of coal temperature are the most critical indicators to realize the accurate prediction of coal spontaneous combustion process. However, due to the concealment of the fire source in the complex confined environment of the goaf, and the coal and rock mass is a poor conductor of heat, it is very difficult to directly monitor the coal temperature. The existing contact temperature measurement method is difficult to adapt to the goaf environment, and there are often false positives and false negatives. Therefore, in

Table 3. Principle and Advantages and Disadvantages of Coal Spontaneous Combustion Monitoring Technology[67−73]

coal spontaneous combustion monitoring technology	peculiarity	scope of application	merits and demerits
beam tube monitoring	small size, easy to install; simple to use and maintain; stable operation	gob area, shallow area, interior area of roadway surrounding rock with different degree of deformation	low cost, simple operation, but easy to be broken or squeezed
wireless AD hoc network temperature measurement	the topological structure of traditional temperature sensor system is changed to adapt to more temperature measurement applications	gob caving space, etc.	Tthe problem of unstable data signal transmission still exists in the practical application process
distributed optical fiber temperature measurement	The optical fiber is used as the sensing medium and the transmission signal medium, and the strain or temperature change of the optical fiber itself or the environment is reflected by measuring the specific scattered light signal in the optical fiber. One optical fiber can measure hundreds of sensing points at the same time	suitable for high temperature, corrosive environment, etc.	Antielectromagnetic interference, high sensitivity, lightweight, small size, low cost. However, the optical cable is easy to be damaged by aging and may have partial discharge problems.
coal spontaneous combustion multiparameter wireless monitoring system	a wireless multiparameter monitoring system integrating temperature and humidity, gas and pressure difference sensors	goaf working face, two roadways, old goaf closed wall, etc.	Online continuous detection of temperature field change in goaf under harsh environment can be realized.

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Table 4. Test Method of Coal Natural Tendency at Home and Abroad[76−80]

nation	research unit	test method	main bases
China	Fushun Branch of Coal Science General Hospital	chromatographic oxygen identification	National standard, GB/T 20104−2006
Britain	University of Nottingham/ Strathclyde/Aberdeen	adiabatic oxidation/DSC thermal analysis/HR method and micro calorimetry	form standardized test procedures, establish IRH, TTR and other indicators identification system
America	Bureau of Mines	abscisic heat and static oxygen absorption method	SHT index and oxygen intake were measured respectively
Poland	University of Krakow	high temperature activation energy method	National Standard, PN-93/G-04558
Australia	Mining Safety Research and Testing Center	R70 index gas composition analysis	commercial test phase
India	Central Mining and Fuel Research Institute	improved cross-point temperature method	a variety of Indian coals were tested using Kirov's method
Turkey	University of Middle East Technical	cross point temperature method	the most common identification method for determining the tendency of spontaneous combustion of coal
NZ	University of Auckland	improved cross-point temperature method	CPT values of various materials were tested
Russia	Saint Petersburg Mining University	Russian U-index	a variety of coal samples, a variety of experimental test results
South africa	University of the Witwatersrand	Wits-Ehac index/Wits-CT index	
New Zealand		R70 index gas composition analysis	
other methods		yerage heating rate (AHR), Feng, Chakravorty, and Cochrane (FCC) liability index and slope of the time−temperature curve on the XPT	

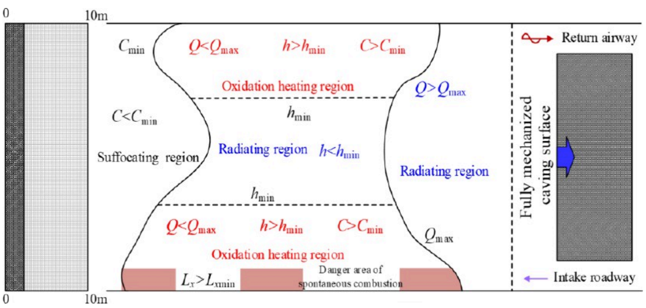

Figure 8. Determination map of spontaneous combustion risk area of goaf in fully mechanized caving face.

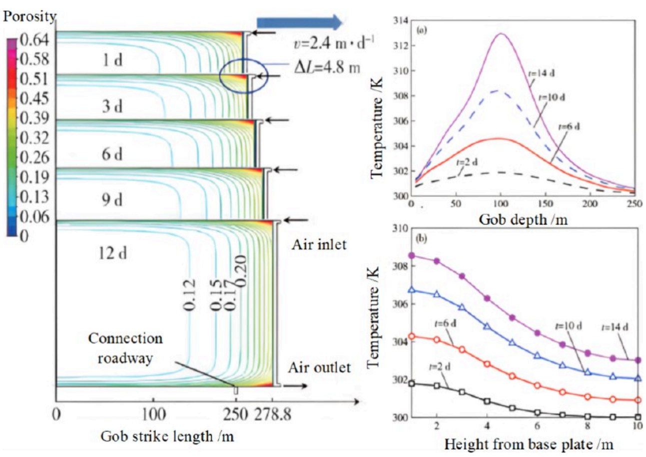

Figure 9. Spatiotemporal evolution process of temperature field in goaf Reprinted with permission from ref 84. Copyright 2016 University of Science and Technology Beijing.

terms of the early prediction of coal spontaneous ignition, domestic and foreign scholars have done a lot of relevant research,[91−94] and proposed the optimization principle of

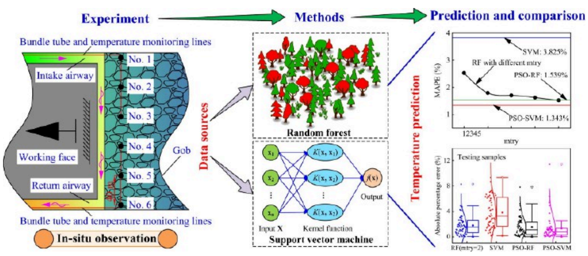

Figure 10. Prediction of high temperature heat source in goaf by machine learning algorithm. Reprinted with permission from ref 87. Copyright 2019 Elsevier.

different coal spontaneous ignition indicator gas indicators, forming CO and its derivative indicators, C_2H_4, C_2H_2 as the main indicators. A comprehensive index system for coal spontaneous ignition prediction with chain alkane ratio, enane ratio, Graham fire coefficient, and temperature as auxiliary indexes.

Liang et al.[95] made a comprehensive review on the gas index prediction methods of coal fire disasters at home and abroad, investigated the most commonly used indicators for spontaneous coal combustion prediction in major coal-producing countries, as shown in (Table 5).

In China, CO, C_2H_4, and C_2H_2 are mainly used as the main gas indicators, and $CO/\Delta O_2$ is used as the main gas index. C_2H_6/CH_4 is used as auxiliary gas index to predict spontaneous combustion of coal. Luo et al.[96] studied the natural ignition indicator gases of various coal types, and concluded that the ethylene or enane ratio should be the preferred index for the low metamorphic coals such as lignite, long flame coal, gas coal, and fat coal. For coking coal and lean coal, CO concentration should be the preferred index, and ethylene or enane ratio can be selected as the auxiliary index. High metamorphic anthracite can only choose CO concentration as the preferred index. Deng et al.[97] determined that CO concentration, second fire coefficient R_2, and streptane

Table 5. Gas Index for Predicting Spontaneous Combustion of Coal Used in Major Coal Producing Countries[76−79,95]

nation	main index	complementary indicator
China	CO, C_2H_4, C_2H_2	$CO/\Delta O_2$, C_2H_6/CH_4
Australia	CO, H_2	$CO/\Delta O_2$
America	CO, H_2	$CO/\Delta O_2$
India	CO, $CO/\Delta O_2$	C/H
Britain	CO, C_2H_4	$CO/\Delta O_2$
Russia	CO	C_2H_6/CH_4
Japan	CO, C_2H_4	$CO/\Delta O_2$, C_2H_6/CH_4
Poland	CO	$CO/\Delta O_2$
Germany	CO	$CO/\Delta O_2$
France	CO	$CO/\Delta O_2$
South Africa	CO	C/H

ratio were used as the primary indicators, and CH_4, C_2H_4, and C_2H_6 concentrations, first and third fire coefficients R_1 and R_3, and alkene−alkane ratio were used as secondary indicators. Wang et al.[98] studied indexes such as $\varphi_{CO} + \varphi_{CO2}$, $\varphi_{CO}/\varphi_{CO2}$, Graham index, $\varphi_{C2H4}/\varphi_{C2H6}$, $\varphi_{C2H6}/\varphi_{CH4}$ of different coal seams in the whole mine, and determined the prediction priorities of indexes at different stages of spontaneous combustion by using gray correlation analysis method. By combining the qualitative analysis of indicator gas and the quantitative determination of supplementary indicators, Guo et al.[99] predicted the trend of mine fire, and carried out the prevention and control measures based on this, and achieved good results. In addition, Ma et al.[100] constructed a new index characterizing the rate of coal oxidation reaction-DO, which is the ratio of oxygen consumption per unit time to total oxygen consumption, and used this index to forecast the degree of coal oxidation.

With the continuous enrichment of coal spontaneous combustion prediction technology and principle, relevant scholars have designed and developed high-precision sensors and monitoring equipment, advanced data acquisition and processing system, intelligent early warning and emergency response system, coal pile management and control equipment, remote monitoring and management system, explosion-proof and fire-fighting equipment and other technical equipment, which can effectively improve the safety of coal mines and storage places, reduce the incidence of spontaneous combustion accidents, protect the safety of people's lives and property, and promote the sustainable development of coal industry.

3.4. Coal Spontaneous Combustion Early Warning Technology. Domestic and foreign scholars have carried out a large number of studies on the monitoring, prediction, and prediction technology and methods of coal spontaneous combustion, and have obtained fruitful results. However, due to the unclear nonlinear gradient mechanism of coal spontaneous combustion process, the temperature threshold of coal spontaneous combustion stage is not clear, and the corresponding relationship between coal temperature and marker gas is not clear, which brings great difficulty to the accurate prediction and scientific early warning of coal spontaneous combustion. At present, there are few reports on the research of coal fire disaster warning. Ye et al.[101] believes that spontaneous combustion of coal pile has phased characteristics through experiments and tests. On the basis of the temperature index, he established the prediction criteria for spontaneous combustion and overburning of coal body, and developed an early warning platform to implement corresponding measures for coal pile at different temperature stages, so as to realize the early warning of spontaneous combustion of coal pile and the optimization of coal pile into the furnace. Tan et al.[102] divided the spontaneous combustion process into four warning levels based on the initial coal oxidation temperature and the characteristic temperature point of spontaneous combustion of coal. Through comprehensive correlation analysis of the ratio of CO and carbon oxide in the upper corner and goaf, a four-level warning mechanism was determined and a detailed warning process was proposed. Ren et al.[103] divided the spontaneous combustion process of coal into 6 levels according to the risk, determined the functional relationship between marker gas and coal temperature through the Logistic model, and believed that this model could provide data support for the development of intelligent early warning software for spontaneous combustion of coal. Aiming at the classification warning and active prevention and control methods of spontaneous coal combustion, this research group conducted thermogravimetric analysis, programmed temperature rise at different scales (8.5 kg, 1.0 kg, 0.3 kg coal samples) and spontaneous ignition experiments (15.0t, 1.5t, 1.0t, 0.8t, 0.4t coal samples) according to the group mutation theory of spontaneous coal combustion process. The nonlinear gradient mechanism of coal spontaneous combustion

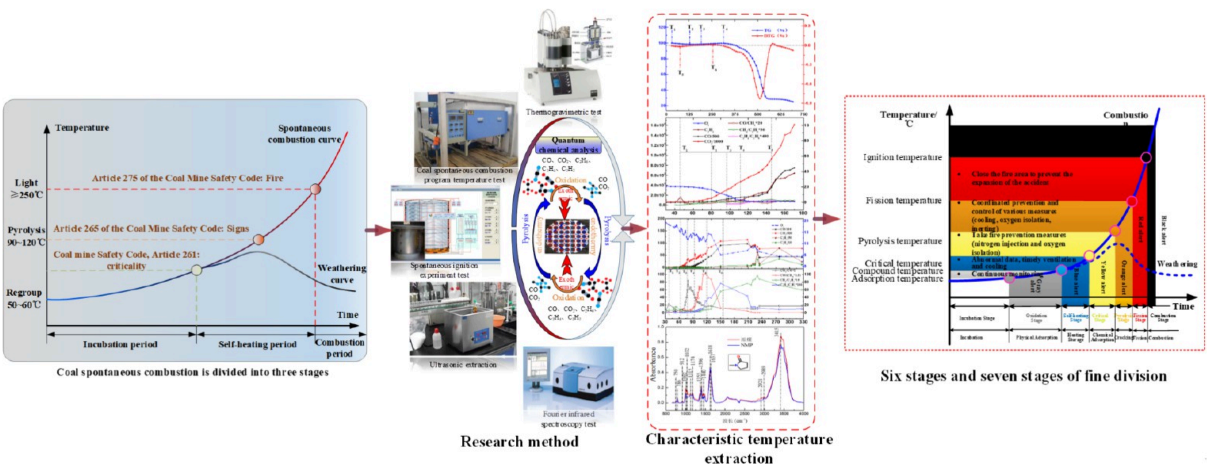

Figure 11. Realization path of coal spontaneous combustion classification early warning method.

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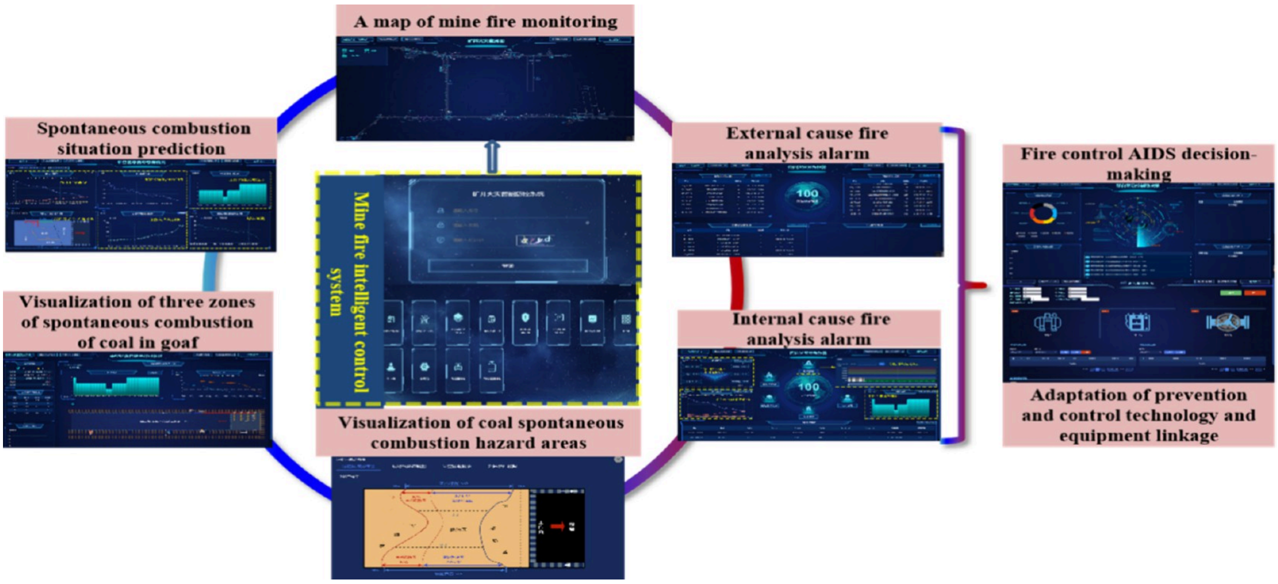

Figure 12. Intelligent monitoring and warning software for spontaneous combustion of coal.

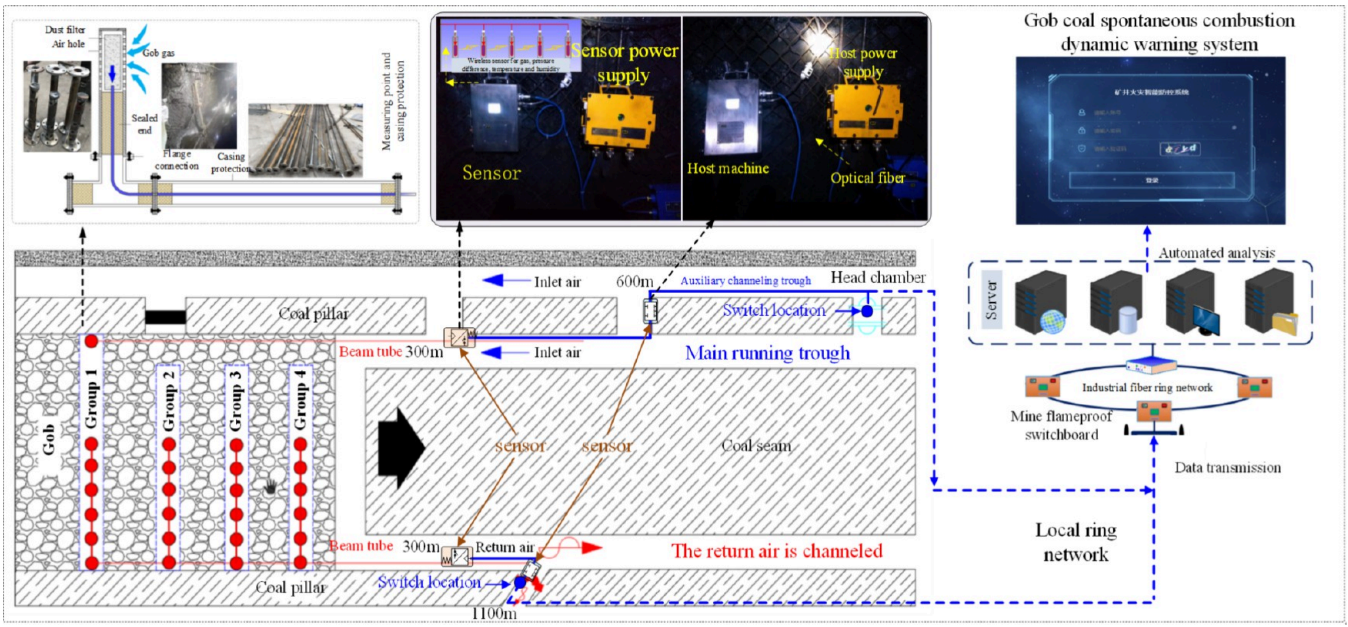

Figure 13. Applicant ion scenarios of nine fire intelligent monitoring and early warning system.

process, temperature threshold of fine stage division, corresponding relationship between coal temperature and indicator gas, gas classification warning index and critical value are studied, and the characteristics of coal spontaneous combustion indicator and indicator gas cause (oxidation and pyrolysis), instrument detection (major and micro), experimental test, and field monitoring environment are analyzed. Six gas characterization indexes of coal spontaneous combustion temperature (CO, O_2, $\Delta CO/\Delta O_2$, C_2H_4, C_2H_2, C_2H_4/C_2H_6) were selected and combined with field observation data, the six-level warning criteria and gas characterization parameter threshold of coal seams prone to spontaneous combustion were determined,[104,105] and accurate early warning of coal seams prone to spontaneous combustion was realized. The quantitative theoretical basis of 261 critical articles, 265 warning articles, and 275 fire articles in coal mine Safety Regulations is clarified, as shown in Figure 11.

In terms of coal spontaneous combustion monitoring and early warning system, Xi'an University of Science and Technology has designed and developed MHJC-V2.0 intelligent monitoring and early warning software, which integrates functions of intelligent analysis and alarm of monitoring data, external fire analysis and alarm, visualization of three zones of spontaneous combustion of goaf coal, and prediction of spontaneous combustion of goaf coal and other modules,[106] as shown in (Figure 12).

It can realize real-time monitoring of coal spontaneous combustion in key areas such as goaf, goaf sealing, and adjacent goaf. According to the actual requirements of the mine site, the coal spontaneous combustion dynamic early warning system has been designed and built, including five

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Table 6. Principle and Advantages and Disadvantages of Detecting Technology of Coal Spontaneous Combustion[121−128]

detection type	detection technique	detection principle and method	advantage	shortcoming
direct probe method	temperature sensor embedded; temperature measurement optical fiber embedded	The location temperature of the measuring point in the goaf is directly obtained, and the signal is transmitted by wired or radio waves, and then transformed into the physical quantity display related to temperature.	In situ detection can be realized, and the measurement results can directly reflect the spontaneous combustion state of coal, and the method is simple and fast.	The effective measurement range is small, affected by environmental conditions, and the reliability is poor.
geophysical method	magnetic detection	The magnetic properties of rocks at high temperature are significantly enhanced, which leads to surface magnetic anomalies. The location of fire source and the range of fire area are determined by the magnetic variation data obtained by arranging survey lines.	fast detection speed, good anti-interference, stable performance, reliable work, economy	The detection depth and resolution are not enough, and it is not sensitive to the initial coal fire.
	infrared thermal imaging detection	Coal combustion produces a large amount of thermal infrared radiation, the surface radiation field is detected, and the internal changes of the detector are determined.	wide applicability and high flexibility	The data is the surface data of the probe, and the error is large, the operation is complicated and the cost is high.
	geological radar method	Electromagnetic wave propagation in different media produces different attenuation phenomena, the interface will appear reflected waves, when the conductivity of the high temperature area of the coal seam is reduced, there will be no obvious reflection interface, and the reflection waveform is messy.	The method is simple and rapid.	The attenuation is too fast, it is difficult to distinguish the structure, the hidden danger of spontaneous combustion and the source of spontaneous combustion, and the accuracy of quantitative analysis is lacking.
	resistivity detection method	On the basis of the resistivity difference between coal and rock, the apparent resistivity change of coal and rock section is calculated through the electrode monitoring data, and the burial depth and range of the fire area are determined.	The method is simple and rapid.	It is greatly affected by the terrain and surrounding electrical appliances, and cannot achieve accurate positioning.
	spontaneous potential method	Coal seam combustion results in abnormal SP.	high detection efficiency	poor anti-interference
	remote sensing method	aerospace thermal infrared remote sensing	large detection range and rich data	It is greatly affected by the depth of coal seam.
chemical exploration method	isotope method for radon measurement	The spontaneous combustion of underground coal forms a high temperature and high-pressure environment, which speeds up the rate of radon precipitation from the formation and upward migration, resulting in surface radon anomalies	The operation is simple and low cost, and the horizontal position of the underground fire source can be roughly determined.	The detection accuracy is low, easy to be affected by geological conditions, can not determine the elevation of the fire source.
	ground gas determination method	On the basis of the pressure difference and molecular diffusion phenomenon, the result anomaly map of the ground gas is drawn, and the approximate location of the fire source and the degree of combustion are determined by combining the indicator gas.	wide applicability	The basic condition is positive pressure ventilation, which is greatly affected by the mining depth, the nature of overlying strata and the surface airflow, and the detection accuracy is poor.
	underground gas determination method	Coal spontaneous combustion gas product component concentration and temperature corresponding law, combined with the index gas to determine the degree of coal spontaneous combustion.	wide applicability, strong operability, low cost	It is impossible to judge the exact location and development speed of the fire source, and there are many interfering factors.
	two-element tracer gas method	Pyrolysis of $CClBrF_2$ occurs at high temperature, and SF_6 is stable. Comparing the concentration changes of the two gases, we can determine whether there is a fire source on the tracer gas flowing through the line.	The result is reliable and simple.	It is difficult to determine the location and range of the fire source, and the pyrolysis temperature of $CClBrF_2$ is above 550 °C, which has limitations in practical application.
boring method	method for determination of environmental parameters in borehole	The environmental parameters and physical and chemical information on coal and rock in the borehole can be obtained by the borehole coring or temperature sensor to determine the location of the high-temperature area.	The influence of environmental conditions is small and the detection accuracy is high.	large amount of engineering, high cost, and low efficiency
noncontact detection method	acoustic measurement of coal temperature	The temperature or temperature field is solved by using the rate change caused by the sound wave propagating in the gas medium and the gas temperature.	can realize the complex geological structure of loose coal in the area of abnormal temperature point fast accurate determination	The applicability of the laboratory model to gob field needs further study.

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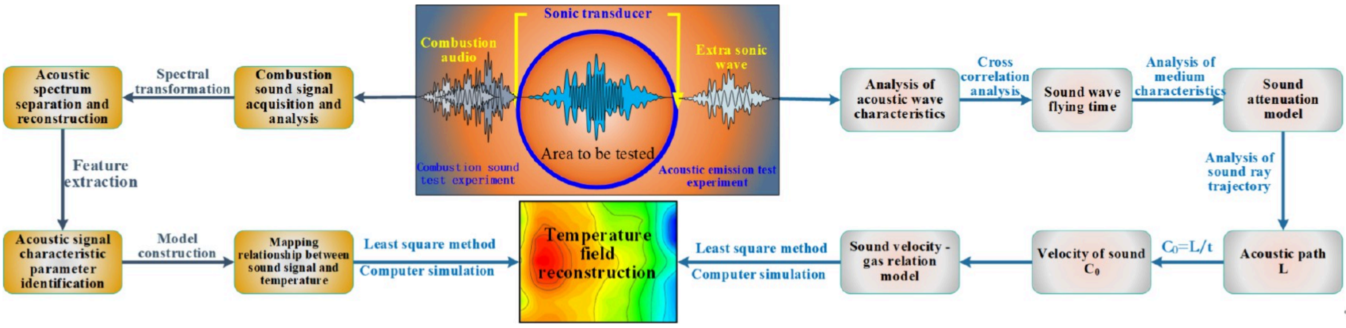

Figure 14. Principles of acoustic temperature measurement and fire detection technology. Reprinted with permission from ref 115. Copyright 2023 American Chemical Society.

modules, such as data storage center, service configuration center, alarm prevention and control center, and learning and training center.

In addition, Deng et al.[107] from Xi'an University of Science and Technology designed a wireless sensor based on radio frequency technology and developed a wireless sensor monitoring system based on Internet of Things technology for underground coal spontaneous combustion, which can adapt to the complex underground environment and realize online monitoring of hidden dangers of coal spontaneous combustion in deep goaf. Guo et al.[106] built a classification early warning model of Class I coal seams prone to spontaneous combustion by combining the characteristic points of the index curve with the mechanism of spontaneous combustion of coal, and determined the relevant early warning indicators and thresholds. Design and develop ZDC7 mine fire intelligent monitoring and warning system, mainly including mine safety multiparameter wireless sensor (GD7), mine safety wireless monitoring host (ZDC7-Z), and intelligent management and control software platform. The system can realize real-time monitoring of coal spontaneous combustion characteristic information in key areas such as goaf area, goaf area, roadway high-rise area, and adjacent air side of underground working face. The application scenario is shown in (Figure 13). It has the functions of intelligent perception, information fusion, data mining, and real-time early warning and decision support, which can realize real-time online monitoring and intelligent early warning of coal spontaneous combustion fire, and assist coal mine engineers and technicians to ensure safe and green mining.

4. RESEARCH PROGRESS OF COAL FIRE DISASTER CONTROL TECHNOLOGY

After more than 60 years of development, coal mine fire prevention and control technology has made remarkable progress in fire source detection, coal fire disaster prevention, and control technology equipment and materials. In recent years, the concept of "prevention−control−treatment" three-in-one hierarchical coordinated prevention and control of coal fire disaster prevention has gradually formed.

4.1. Fire Source Detection Technology. Due to the complexity of coal spontaneous combustion environmental factors, concealment of ignition location and movement characteristics, coal fire disaster prevention and control has a certain uncertainty. As the basis of coal fire disaster prevention and control, concealed fire source detection has always been a worldwide problem to be solved in the coal industry.

With the continuous development of detection technology, domestic and foreign scholars have carried out a large number of studies, and obtained a variety of feasible methods for the detection of coal spontaneous combustion ignition sources or high temperature areas. According to the detection principle, the detection technology of fire sources is divided into four categories: direct exploration, geophysical exploration, geochemical exploration, and drilling method. Direct exploration method refers to the method of directly measuring the temperature of goaf. At present, the temperature of goaf is directly obtained through the measurement points such as embedded temperature sensor or optical fiber in goaf.[108,109] Geophysical exploration technology is mainly based on the change of geophysical characteristics information in the high temperature area of the goaf, observing the change of indicators in the area to be measured by laying a survey network, and researching and determining the location and development status of the fire area.[110] Chemical exploration is to capture the abnormal chemical composition of the goaf through the instrument to release chemical substances, and use the special reaction of the substance to delineate the high-temperature region.[111] The drilling method mainly obtains the physical and chemical information on temperature, carbon monoxide, and coal rock or the environmental parameter characteristics of the final hole location through drilling coring analysis, and determines the state of the fire area based on comprehensive comparison and analysis.[112] The development of fire source location detection technology has the characteristics of diversification. The principles and advantages and disadvantages of various detection technologies are shown in (Table 6).

In this stage, radon method, infrared thermal imaging method, borehole temperature measurement, high-density electrical method and magnetic method are relatively common detection technologies. In addition, domestic and foreign scholars are also committed to exploring new fire source detection methods and detection technologies. For example, relevant scholars have learned from the wide application of acoustic temperature measurement technology in agriculture, industry and atmospheric space, and carried out basic research on the detection of temperature field of heated loose coal by acoustic method.

Acoustic temperature measurement technology, as a new acoustic detection technology, is based on the fact that the sound velocity in the propagation medium is the first function of the absolute temperature of the medium, and uses the rate change caused by the effect of the sound wave on the gas temperature when propagating in the gas medium to solve the

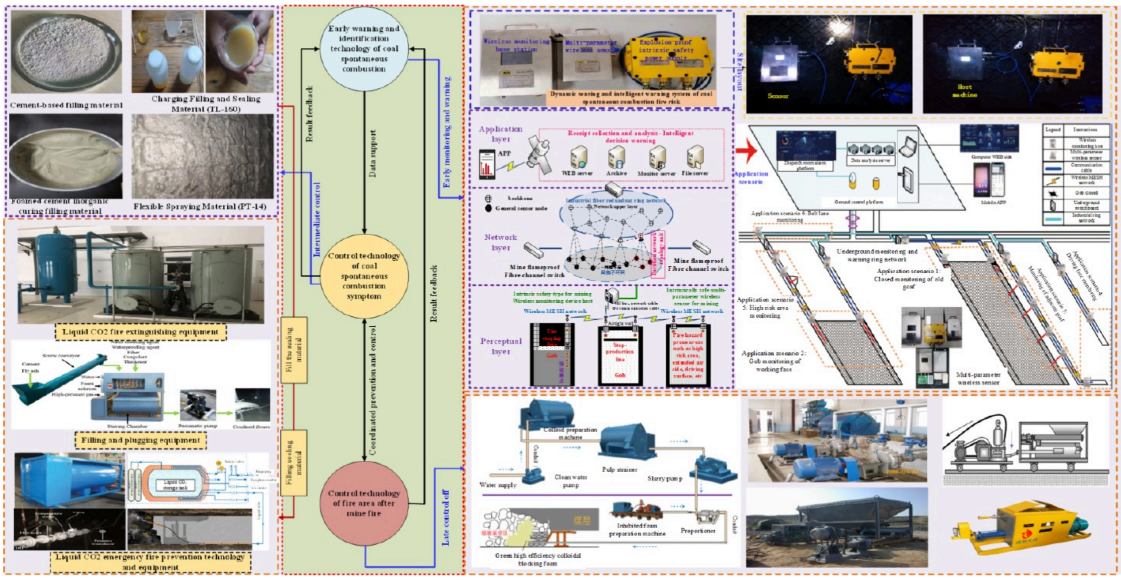

Figure 15. Fire extinguishing technology and equipment diagram.

temperature or temperature field. The principle of acoustic temperature measurement is shown in (Figure 14). It has significant advantages such as high measurement accuracy, wide temperature measurement range, large measurable space, noncontact, real-time continuous, and so on. Guo et al.[113,114] compared and analyzed the existing coal temperature detection technologies, and explored the acoustic temperature field reconstruction method based on the coal body as the background, which provided a new idea for the accurate detection of concealed fire sources in goaf. Guo et al.[115] applied the acoustic temperature measurement method to coal particle temperature measurement, built a sound absorption test system for loose coal, determined that the linear sweep signal was the best sound source signal for acoustic temperature measurement of coal, and provided a parameter basis for the application of acoustic temperature measurement in coal.

Professor Deng et al.[116] has studied the propagation characteristics of sound waves in loose coal under three atmospheres. The experimental results show that the propagation of sound waves is carried out in the pores of coal, which provides a theoretical basis for the application of acoustic temperature measurement in loose coal. By combining Matlab simulation, theoretical analysis and experimental testing, Guo et al.[117] studied the distortion characteristics of the pseudorandom sequence sound source signal, determined the best processing method of the signal, and successfully applied it to the temperature measurement of loose coal body. Deng et al.[118] designed and built an experiment platform to study the influence of gas properties and sediment particle size on sound propagation characteristics, and determined the influence law of sound wave propagation frequency and time delay estimation algorithm in sediment particles on sound propagation, providing references for subsequent coal sediment experiments. In order to explore the propagation characteristics of sound waves in pulverized coal, Yang et al.[119] actually built a pulverized coal acoustic propagation experimental system, carried out research on acoustic attenuation characteristics with different acoustic frequencies, and determined the acoustic frequency band and delay estimation algorithm suitable for detection in pulverized coal. Guo et al.[120] built an experimental system for measuring biomass temperature with acoustic method. By introducing characteristic factors, they studied the propagation velocity of sound waves in biomass at different temperatures, and the results showed that there was a good inversion accuracy between sound velocity and coal temperature in the range from 22 °C to 48.9 °C.

4.2. Technical Equipment and Materials for Coal Spontaneous Combustion Prevention and Control. According to the coal-oxygen recombination mechanism, the abandoned coal in the goaf will oxidize slowly and turn into spontaneous combustion under appropriate conditions (coal with a tendency to spontaneous combustion, floating coal with a certain accumulation thickness, suitable air leakage conditions, good heat storage environment, and a certain time). Therefore, the prevention and control principle of coal fire disaster is based on the necessary conditions of coal oxidation. In the process of coal seam mining, one or more conditions are destroyed to delay or prevent its further oxidation spontaneous combustion.

In the 1990s, domestic coal mining enterprises began to use a large number of grouting technologies represented by fly ash, shale mud, coal preparation tailings mud, retarding agents, and retarding mud, as shown by the inert gas represented by N_2. The schematic diagram of fire extinguishing technology and equipment is shown in (Figure 15).

In terms of materials, domestic and foreign scholars have improved traditional prevention and control materials and developed many new materials to prevent coal spontaneous combustion through physical and chemical methods. These materials play a synergistic role by oxygen absorption, moisture cooling, inhibition or interruption of chain reaction, etc., to delay the oxidation process of coal and then inhibit coal spontaneous combustion.[129]

Commonly used materials include filling and sealing materials, slurry materials, physical, chemical, new inhibitors, inorganic, organic, and composite colloidal materials. In addition, studies in recent years have shown that liquid inert gas (CO_2, N_2) has obvious effects in fire prevention and

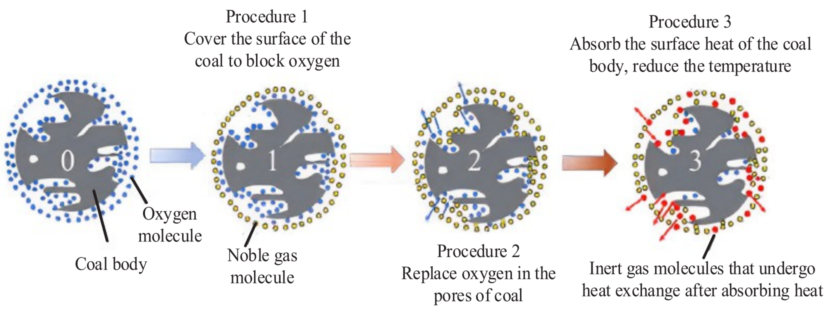

Figure 16. Inert gas flame retardant mechanism diagram. Reprinted with permission from ref 130. Copyright 2020 China University of Mining &Technology.

Table 7. Coal Spontaneous Combustion Prevention and Control of the Main Materials and Mechanism[131−138]

preventive measure	materials		action mechanism
filling and plugging	inorganic curing foam, foam concrete		**Oxygen control:** block air leakage, avoid contact between coal and oxygen, inhibit coal oxidation
multiphase inert gas	CO_2, N_2		**Oxygen control, cooling, physical resistance:** liquid phase gasification volume increases to dilute oxygen, absorb a lot of heat, adsorption on the surface of coal to block the contact between coal and oxygen, competitive adsorption to replace the oxygen in the coal, coal surface and pores in the inert gas absorb part of the heat during the coal oxidation process
slurry material	fly ash slurry, yellow mud		**Oxygen control and cooling:** water-containing slurry wraps the coal body, isolating oxygen, water evaporation absorbs heat, and water enters the coal body to produce water lock effect
retarder	physical inhibitor	absorbent salts, polymers, foam materials, aerosols, pastes	**Oxygen control and cooling:** the blocking agent covers the coal body, isolating oxygen, water evaporation absorbs heat, and water enters the coal body to produce water lock effect
	chemical inhibitors	antioxidant, alkaline, acidic, ionic liquids	**Interrupt the chain reaction:** the inhibitor reacts with the active group of coal to produce a stable intermediate product, inverts the activity of the functional group of the oxygen reaction of coal, gradually interrupts the activation reaction chain, and weakens the oxidation reaction of coal
	new inhibitor	composite inhibitor, microcapsule combination, inorganic nano	**Oxygen control, cooling, interrupt the chain reaction:** overcome the defects of a single inhibitor, and have the flame retardant properties of physical and chemical inhibitors
colloidal material	inorganic gels	inorganic foamed gel material, new FSA microporous colloidal flame retardant, fly ash colloidal, ammonia-free gel, plastic water glass gel, etic	**Oxygen control and cooling:** absorb a lot of heat by heat, realize the cooling of coal itself, and achieve the purpose of oxygen isolation
	organogels	new polyvinyl alcohol oxygen insulating gel, temperature sensitive hydrogel, sodium carboxymethyl cellulose/aluminum citrate gel for mining, CMC/ZrCit/GDL gel, P(AA-*co*-AM) gel, new high water absorption fire extinguishing gel	
	complex colloid	suspended sand colloid, gelled colloid, ternary composite colloid, new water glass/polymer composite gel	

control,[131] mainly because liquid inert gas vaporizes and absorbs a lot of heat during contact with coal. It also plays a multifactor role such as oxygen isolation, adsorption inverting, and its flame retardant mechanism is shown in (Figure 16).

Due to the innovation of nitrogen production technology, N_2 has been widely used as a fire-fighting material, and has become a traditional inert gas prevention material. However, liquid N_2 is relatively less used in coal mining enterprises due to harsh construction conditions, and CO_2 molecules are more dense than air and easy to deposit at the bottom, and CO_2 adsorption and flame retardancy are good, which can better dilute low-level gas and inhibit coal body. It is often used by coal mining enterprises for coal fire disaster emergency. The main materials and mechanism of action are shown in (Table 7).

In addition, some new technologies are being used in mine fire prevention and control. Li et al.[139] learned from the frozen soil hot rod heat transfer technology and carried out research on the hot rod heat transfer technology of coal body, as shown in (Figure 17). Experimental tests and field applications were carried out on the ground spontaneous combustion gangue

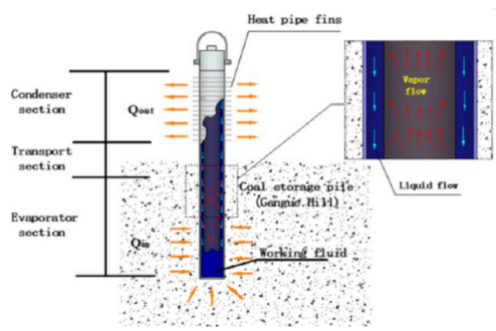

Figure 17. Schematic diagram of hot rod heat transfer. Reprinted with permission from ref 139. Copyright 2018 Springer.

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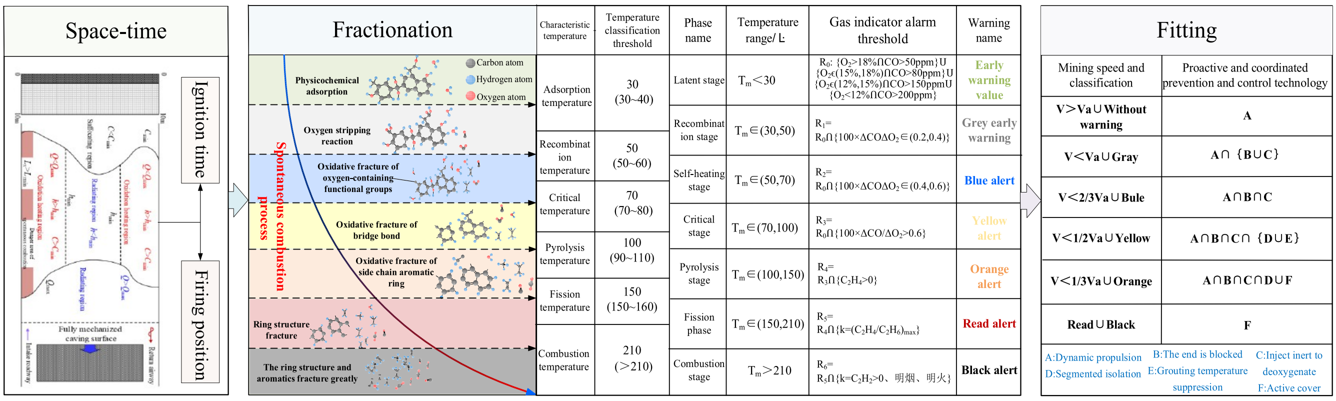

Figure 18. "Space-time—Grading—Adaptation" coal spontaneous combustion disaster prevention and control system.

mountain and coal field fires, and the ability of heat transfer of hot rod to coal body was investigated.

4.3. "Time–Space–Classification–Adaptation" Coordinated Prevention and Control Technology System. The technical equipment and materials for coal fire disaster prevention and control have been comprehensively developed, but the difficult problem of what technology should be adopted to prevent and control coal spontaneous combustion in goaf has not been effectively solved at present, which often leads to the blindness of disaster prevention and control and causes a lot of waste of resources. This research group aims at accurate monitoring, situation prediction, and hierarchical prevention and control of coal spontaneous combustion hidden fire sources. Based on dynamic and static characteristics of coal spontaneous combustion danger areas, combined with regional characteristics, warning time series, risk level, detection means, prevention and control measures, and other factors, the research group aims to prevent and control coal spontaneous combustion disasters by zoning, classification, time-sharing, and coordinated adaptation. The technical system of monitoring, early warning, and emergency prevention and control of spontaneous coal combustion in mines with "spatiotemporal, classification-adaptation" was constructed,[105] as shown in (Figure 18).

It has been studied that the molecular side chain, bridge bond, aromatic ring, and other groups with different oxidation and pyrolysis characteristics of coal at different temperature stages occur in sequence of physical oxygen absorption, chemical oxygen absorption, oxidation reaction, group activation, pyrolysis bond breaking fission ring breaking, gas–solid combustion, and other mutation reactions, which is the root cause of the unstable evolution of the spontaneous combustion process. There are 6 temperature mutation points in the nonlinear gradual process of coal spontaneous combustion, which can be divided into 7 stages: latent, composite, self-heating, active, pyrolysis, fission, and combustion, and the six-level warning gas index threshold is determined.

According to the scope and grade of the danger area of spontaneous combustion of abandoned coal in goaf, the minimum advancing speed of the coal working face determined according to the "three zones" of spontaneous combustion of coal in goaf and the danger area, matching the actual advancing speed of the coal working face and combining the classification warning of spontaneous combustion of coal. The coal spontaneous combustion prevention and control methods of "dynamic promotion, end plugging, inert oxygen injection, stage isolation, grouting temperature suppression, active cover" and other technical means are coordinated, and the coal spontaneous combustion prevention and control technical means are selected from the coal spontaneous combustion prevention and control time and key areas, and according to the warning results of different levels of coal spontaneous combustion, so as to realize the transformation of coal spontaneous combustion hidden dangers from passive management to active, efficient, and accurate prevention and control.

5. MAIN PROBLEMS AND THE FUTURE DEVELOPMENT TREND

After decades of efforts by researchers and coal mining enterprises and institutions, the theory of spontaneous combustion of coal has been greatly enriched, coal fire disaster prevention technology has been greatly developed, there are a series of mine fire prevention monitoring equipment and materials with excellent performance, on-site disaster prevention and control has also achieved good results, caused by spontaneous combustion of coal mine disaster accidents are decreasing year by year. However, in recent years, heavy coal fire accidents also occur, causing huge loss of life and property and serious negative social impact, coal mine spontaneous combustion fire prevention and control forms are still severe, coal fire prevention and control technology still have a lot of technical problems and need to be gradually solved in the future development. It mainly includes the following aspects:

5.1. Basic Theory of Spontaneous Combustion of Coal Is Still to Be Perfected. The mechanism of coal spontaneous combustion and the spatiotemporal evolution characteristics of the coal oxidation process are the basis for accurate early warning of coal fire disasters. Scholars have conducted a large number of studies on the macro and micro processes of coal spontaneous combustion, including the molecular structure of coal in the micro aspect, the coal–oxygen complex chain reaction process, and the characteristics of the "heat–gas–solid" reaction in the macro aspect. These studies have basically defined the reaction process of coal–oxygen composite. It provides some theoretical support for coal fire disaster prevention, but due to the complexity of coal molecular structure and the limited research methods and technologies of the existing micromechanism of coal spontaneous combustion, there are some limitations in accurately revealing the mechanism and stage characteristics of coal spontaneous combustion. In the future, it is necessary to determine the change law of the microscopic structure of coal spontaneous combustion process, and conduct in-depth studies on the nonlinear and abrupt characteristics and the coupling mechanism of internal and external factors in the process of coal spontaneous combustion, so as to master the thermal dynamic characteristics, phase characteristics, and characterization parameters of the low-temperature oxidation stage, and then fully grasp the occurrence and evolution of coal spontaneous combustion.

5.2. Monitoring and Early Warning Technology and Equipment Need to Be Improved. At present, a coal spontaneous combustion early warning method based on indicator gas and coal temperature monitoring has been basically established, the coal spontaneous combustion process has been finely divided and a hierarchical early warning system has been constructed. Accordingly, optical fiber temperature measurement, wireless network temperature measurement and environmental multiparameter monitoring systems have been developed, and the monitoring and early warning technology has been greatly improved. However, there are still drawbacks in the accuracy and reliability of equipment monitoring. With the improvement of mechanization level and the advancement of intelligent mine construction, monitoring and early warning should tend to develop in the direction of intelligent dynamic monitoring based on automatic monitoring technology combined with big data analysis, establish a dynamic visualization prediction technology of coal spontaneous combustion that comprehensively considers mine production environment parameters and coal spontaneous combustion characteristic parameters, and develop monitoring and monitoring system equipment that takes into account speed, high precision, and high stability. Realize dynamic monitoring and intelligent early warning of coal spontaneous combustion in mine.

5.3. Fire Source Detection Technology Needs Further Research. The development of fire source detection technology is of great significance to the prevention and control of coal fire disasters, and has formed a diversified development trend based on direct exploration, drilling, geophysical exploration, and geochemical exploration. Although the existing coal temperature detection technology has largely solved the problem of delineating the location or range of high temperature points in the fire area, it is limited by the characteristics of the goaf of coal mine, such as strong concealment, complex air leakage, large space scope, random location of high temperature points, invisible internal state, and other technologies, such as construction cost, construction difficulty, and operability. It is still difficult to achieve rapid and accurate measurement of abnormal temperature point of loose coal in complex geological structure area, and it is difficult to accurately judge the burning degree, fire source location, temperature distribution, and other information on coal field fire. Therefore, in the future research, we should enrich the basic theory of fire detection technology, and seek more efficient and convenient detection methods.

5.4. Technical System of Coal Fire Disaster Prevention and Control Still Needs to Be Improved. In terms of coal fire disaster prevention and control, technical equipment and materials have been widely developed, based on which a three-pronged coal fire disaster prevention and control technical system of "prevention−control−control" has been gradually formed, and an active collaborative prevention and control method of "space−time−classification−adaptation" has been constructed. However, at present, there are still many defects in technical equipment and materials, resulting in a certain impact on the disaster prevention and control effect. On the one hand, the current prevention and control materials are very diversified, and various types of materials have a wide variety, different effects and often have a certain degree of pollution, and the process is not perfect; On the other hand, the degree of intelligence of industrial equipment is low, and the existing device is difficult to achieve the integration of alarm, monitoring and spraying. Therefore, in the future development, we should strengthen the research and development of compound green environmental protection materials combined with prevention and control, and the process equipment should be combined with the increasingly complex mine conditions to upgrade the existing process system and technical equipment, and gradually realize automation and intelligence.

6. SUMMARY AND CONCLUSIONS

The concealment and complexity of coal spontaneous combustion require more comprehensive development of coal spontaneous combustion prevention theory, technology, and equipment. Since 60 years of coal fire disaster prevention and control, although China has made great progress in the theoretical system, monitoring and early warning, and disaster prevention and control. However, with the advancement of mechanization, automation, and intelligent mine construction, a series of new characteristics have emerged in mine coal spontaneous combustion fire, and the prevention and control of coal spontaneous combustion fire is also facing new problems. In the existing research, the precise inhibition and control of coal spontaneous combustion disaster, the evolution model of coal spontaneous combustion under the condition of multifactor coupling in the field, the reliability and stability of intelligent monitoring system, the noncontact detection method of fire source, and the collaborative adaptation of multiple prevention and control techniques are not yet clear. The dynamic visualization prediction technology of coal spontaneous combustion, which comprehensively considers the production environment parameters of the mine and the characteristic parameters of coal spontaneous combustion, has not been explored. The upgrading and development of fire source detection technology and fire prevention and extinguishing equipment, as well as the invention and improvement of green and efficient prevention and control materials need to be further studied. Therefore, the related research on mine fire prevention and control has a long way to go, and it is necessary for coal science and technology workers to continue their efforts in the future work.

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Notes

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■ NOMENCLATURE

q_1	coal oxidation heat release
q_2	heat conduction of coal and rock
q_3	convection heat exchange between air flow and floating coal
$q(T_c)$	heat generated per unit time and unit volume measured at T, J/(cm^3·s)
λ_c	thermal conductivity of coal, J/(cm·s·°C)
n	porosity of loose coal
ρ_g	density of loose coal, g/cm^3,
c_g	heat capacity of loose coal, J/(g·c)
Z_1	width of oxidation zone in goaf
Z_2	width of heat dissipation zone in goaf
L, H	requirements and known perimeter of working face
φ	working face recovery rate, %
$\delta(T)$	production rate of CO gas in coal at temperature T· mol/(cm^3·s)
Q	air supply volume of working face
t	time required for coal to rise from normal temperature to critical temperature
T_o	room temperature
T_{kp}	critical temperature at which coal begins to heat up at an accelerated rate
I_{CO_2}	when the temperature reaches 70 °C, the oxygen concentration index of the outlet has no dimension.
C_{O_2}	oxygen concentration at the outlet of the coal sample tank at 70 °C, %
$I_{T_{cpt}}$	temperature index of coal crossing point under temperature program is dimensionless
T_{cpt}	cross point temperature of coal under temperature-programmed condition, °C.
I	determination index of spontaneous combustion tendency
V_{CO}	CO emission from the working face
α	oxidation correction coefficient of coal left in oxidized zone of goaf
β	modified oxidation coefficient of tropical coal scattered in goaf
C_p	average specific heat of coal from normal temperature to critical temperature
K	oxygen uptake rate constant of coal between $(T - T_{kp})$
Δ_{t_i}	time experienced when the temperature rises from T_i to T_{i+1}
C_{pi}, C_{pi+1}	specific heat capacity of coal at T_i and T_{i+1}
W_{pi}	amount of water evaporation from T_i to T_{i+1}
λ	heat of water evaporation and desorption, with a fixed value of 2.26 kJ/g
u_i	desorption amount of gas at temperature T_i
Q'	heat of gas desorption, and the average value is 12.6 J/ml.
W_p	total moisture content in coal

■ REFERENCES

(1) Xie, K. China's Energy Development for 2035: Strategic Thinking and Suggestions. *Strategic Study of CAE* **2022**, *24*, 1−7.

(2) Xie, H. P.; Wu, L.; Zheng, D. Prediction on the energy consumption and coal demand of China in 2025. *J. China Coal Soc.* **2019**, *44* (7), 1949−1960.

(3) Biswal, S. S.; Gorai, A. K. Change detection analysis in coverage area of coal fire from 2009 to 2019 in Jharia Coalfield using remote sensing data. *Int. J. Remote Sens* **2020**, *41* (24), 9545−64.

(4) Muduli, L.; Jana, P. K.; Mishra, D. P. Wireless sensor network based fire monitoring in underground coal mines: a fuzzy logic approach. *Process Saf Environ. Prot* **2018**, *113*, 435−47.

(5) Chermin, H. A. G.; Van Krevelen, D. W. Chemical structure and properties of coal XVII-A mathematical model of coal pyrolysis. *Fuel* **1957**, *36* (1), 85−104.

(6) Given, P. The distribution of hydrogen in coals and its relation to coal structure. *Fuel* **1960**, *39* (2), 147.

(7) Wiser, W. Reported in division of fuel chemistry. *Preprints* **1975**, *20* (1), 122.

(8) Jin, H. H.; Xu, B. N.; Li, H. Q.; Ku, X. K.; Fan, J. R. Numerical investigation of coal gasification in supercritical water with the ReaxFF molecular dynamics method. *Int. J. Hydrogen Energy* **2018**, *43* (45), 20513−20524.

(9) Cui, X.; Yan, H.; Zhao, P. T. A review on the model construction and analytical methods of coal molecular structure. *J. China University of Mining Technol.* **2019**, *48* (04), 704−717.

(10) Ge, L. M. Oxidation of active groups in coal molecules and spontaneous combustion mechanism of coal. *J. Xian Mining Inst.* **1988**, No. 01, 91−96.
(11) Xu, X. *Determination Theory of Coal Spontaneous Combustion Danger Area Beijing*; Coal Industry Press: Beijing, 2001,42.
(12) Wen, H.; Dai, A. Discuss molecular structure model of describing coal. *Coal Conversion* **2004**, No. 2, 13−18.
(13) Wang, D. *Kinetic Theory and Application of Coal Oxidation*. Science Press: Beijing, 2012.
(14) Yu, M. G.; Jia, H. L.; Yu, S. J.; Pan, R. K. Calculation of micro-structure parameter of Wuda bituminous coal and relationship-analysis between coal structure and coal spontaneous combustion. *J. China Coal Soc.* **2006**, No. 5, 610−614.
(15) Zhang, Y. N.; Liu, C. H.; Song, J. J.; Wang, A. P. Study on transfer law of main functional groups in low temperature oxidation of long flame coal. *Coal Sci. Technol.* **2020**, *48* (03), 188−196.
(16) Zhang, Y. N.; Deng, J.; Yang, H.; Zhao, J. Y.; Wang, C. P. Experimental study of the characteristic features of the microstructure of coal at different coal sorts. *J. Safety Environ.* **2014**, *14* (04), 67−71.
(17) Wang, J. R.; Deng, C. B. The spontaneous combustion theory of coal microcosmic structure and component differences in quantity and quality. *Coal Sci. Technol.* **2007**, No. 12, 1291−1296.
(18) Zhang, Y. T.; Yang, C. P.; Li, Y. Q.; Huang, Y.; Zhang, J.; Zhang, Y. B.; Li, Q. P. Ultrasonic extraction and oxidation characteristics of functional groups during coal spontaneous combustion. *Fuel* **2019**, *242*, 287−294.
(19) Wen, H. Experiment simulation of whole process on coal self-ignition and study of dynamical change rule in high-temperature zone. *Coal Sci. Technol.* **2004**, No. 06, 689−693.
(20) Deng, J.; Xiao, Y.; Li, Q. W.; Lu, J. H.; Wen, H. Experimental studies of spontaneous combustion and anaerobic cooling of coal. *Fuel* **2015**, *157*, 261−269.
(21) Liu, Y.; Wen, H.; Guo, J.; Jin, Y.; Wei, G.; Yang, Z. Coal spontaneous combustion and N_2 suppression in triple goafs: A numerical simulation and experimental study. *Fuel* **2020**, *271*, No. 117625.
(22) Wang, D. M.; Lu, W.; Li, Z. H.; Zhou, F. B. *An Adiabatic Test Device for Simulating Coal Spontaneous Combustion Process*; China University of Mining and Technology: Beijing, 2005.
(23) Jin, Y. F.; Guo, J.; Wen, H.; Liu, W. Y.; Wang, K.; Ma, X. F. Experimental study on the high temperature lean oxygen oxidation combustion characteristic parameters of coal spontaneous combustion. *J. China Coal Soc.* **2015**, *40* (3), 596−602.
(24) Xu, Y. H. *Research on Macro Featured Parameters and Test Methods of Coal Spontaneous Combustion Character*; Xi'an University of Science and Technology: Xi'an 2014.
(25) Liu, W. Y. *Study on Thermal Effect and Adiabatic Spontaneous Ignition Period of Coal Oxidation*; Xi'an University of Science and Technology: Xi'an 2019.
(26) Li, D. W.; Wang, D. M.; Gu, J. J.; Qi, X. Y.; Zhong, X. X.; Huang, B. B. Experiment research on coal physical oxygen sorption law with temperature and particle size variation. *Coal Sci. Technol.* **2008**, No. 2, 42−44.
(27) Deng, J.; Zhang, Y. X.; Zhao, J. Y.; Song, J. J.; Zhang, Y. N. Experiment study on oxidation and activated energy of different particle size coal based on programmed temperature rising. *Coal Sci. Technol.* **2019**, *47* (1), 214−219.
(28) Deng, J.; Deng, Y.; Zhang, Y. T.; Zhang, Y. N. Experimental research on coal sample secondary oxidation and spontaneous combustion properties with moisture contents. *J. Xi'an University Sci. Technol.* **2016**, *36* (04), 451−456.
(29) Zhai, X. W.; Ge, H.; Wang, K.; Wu, S. B.; Wang, T. Y. Research on influences of water soaking-drying on coal spontaneous combustion characteristics and predictive index. *China Safety Sci. J.* **2018**, *28* (5), 68−73.
(30) Hu, X. C. *Micro Physicochemical Properties and Macro Thermal Effect of Coal Influenced by Methane-Containing Environment during Oxidation*; China University of Mining and Technology: Xuzhou, 2017.
(31) Wen, H.; Xu, J. C.; Xue, H. L.; Dai, A. L. Analysis of influencing factors on exothermic effect of coal spontaneous combustion oxidation. *Coal Conversion* **2001**, No. 4, 59−63.
(32) Zhao, J. Y.; Zhang, Y. X.; Song, J. J.; Zhang, Y. N.; Wang, K. Coal spontaneous combustion indicator gases analysis of different temperature stages upon high-temperature and low-oxygen condition. *J. Xi'an Univ. Sci. Technol.* **2019**, *39* (2), 189−193.
(33) Wen, H.; Lu, Y. B.; Liu, W. Y. Experimental study on the risk of secondary oxidation spontaneous combuction of water immerced coal. *Mining Safety Environ. Protection* **2020**, *47* (3), 6−11.
(34) Deng, J.; Zhao, J. Y.; Zhang, Y. N.; Wang, C. P. Experiment on secondary oxidation spontaneous combustion characteristics of low metamorphic degree coal. *Coal Sci. Technol.* **2016**, *44* (3), 49−54.
(35) Zhang, Y. T.; Li, Y. Q.; Deng, J.; Zhang, X. H. Study on catastrophe characteristics of coal spontaneous combustion. *China Safety Sci. J.* **2015**, *25* (1), 78−84.
(36) Zhang, Y. T. *Fractal Oxidation Kinetics and Risk Evaluation of Spontaneous Combustion in Coal Mines*; Missouri University of Science and Technology: Rolla, MO, 2012.
(37) Xu, T.; Wang, D. M.; Xin, H. H.; Qi, X. Y. Experimental Study on the Temperature Rising Characteristic of Spontaneous Combustion of Coal. *J. Mining Safety Eng.* **2012**, *29* (4), 575−580.
(38) Deng, J.; Zhao, J. Y.; Zhang, Y. N.; Wang, C. P. Micro-characteristics of spontaneous combustion of second oxidation with different rank coals. *J. China Coal Soc.* **2016**, *41* (5), 1164−1172.
(39) Deng, C. B.; Wang, J. R.; Zhang, J.; Deng, H. Z. Reaction mechanism of ethylene production during spontaneous combustion of coal. *J. China Coal Soc.* **2008**, No. 3, 299−303.
(40) Wang, J. R.; Chen, Q. W.; Deng, C. B.; Deng, H. Z.; Wang, X. Y. Reaction mechanism of coal spontaneous combustion producing methane. *J. China Coal Soc.* **2009**, *34* (12), 1660−1664.
(41) Wang, J. R.; Deng, H. Z.; Deng, C. B.; Ye, B. Coal spontaneous combustion producing carbon monoxide and water reaction mechanism research. *Comput. Appl. Chem.* **2008**, *8*, 935−940.
(42) Wen, H. *Study on Experimental and Numerical Simulation of Coal Self-ignition Process*; Xi'an University of Science and Technology: Xi'an, 2003.
(43) Xu, J. C.; Deng, J.; Wen, H. Analysis of possible ignition area in goaf of coal face. *J. Xi'an Univ. Sci. Technol.* **1998**, No. 01, 14−23.
(44) Xu, J. C.; Wen, H.; Deng, J.; Zhang, X. H. Study Limit Parameter of Coal Self-ignite. *Fire Safety Sci.* **2000**, No. 2, 14−18.
(45) Di, C. C.; Xin, H. H.; Li, J. S. Research of Prediction Method of Adiabatic Oxidation Time Based on the Propensity of Coal to Spontaneous Combustion. *Sci. Technol. Eng.* **2017**, *17* (21), 1671−1815.
(46) Deng, J.; Xu, J. C.; Xu, T. M.; Zhang, X. H. Test and application of the Spontaneous combustibility parameters of coal. *J. Fuel Chem. Technol.* **2001**, No. 6, 553−556.
(47) Zhang, D.; Yang, X. S.; Deng, J.; Wen, H.; Xiao, Y.; Jia, H. Research on coal spontaneous combustion period based on pure oxygen adiabatic oxidation experiment. *Fuel* **2021**, *288*, No. 119651.
(48) Yu, M. G.; Huang, Z. C.; Yu, C. P. Mathematic model for calculating the shortest coal spontaneous combustion time. *Coal Sci. Technol.* **2001**, No. 05, 516−519.
(49) Bai, M. B.; Cai, G. B.; Gao, J. W.; Wang, Z.; Zhang, J. Z.; Yue, N. F. Study on "Three Zones" of Coal Spontaneous Combustion in Goaf of Fully Mechanized Mining Face Based on FLUENT Numerical Simulation. *Coal Technol.* **2020**, *39* (11), 143−146.
(50) Ma, L.; Guo, R. Z.; Wu, M. M.; Wang, W. F.; Ren, L. F.; Wei, G. M. Determination on the hazard zone of spontaneous coal combustion in the adjacent gob of different mining stages. *Process Safety and Environmental Protection* **2020**, *142*, 370−379.
(51) Zhai, X. W.; Ma, L. J.; Deng, J. Study and Application of CO Content Prediction Model to Upper Corner of Coal Mining Face. *Coal Sci. Technol.* **2011**, *39* (11), 59−62.
(52) Ma, L.; Ren, L. F.; Han, L.; Ai, S. W.; Zhang, L. R.; Liu, Y. Y. Experiment study on partical size affected to coal spontaneous combustion limit parameters in goaf. *Coal Sci. Technol.* **2015**, *43* (06), 59−64.

(53) Zhang, Y. T.; Yang, J.; Li, Y. Q.; Shi, X. Q.; Zhang, Y. B.; Lin, G. C. Effects of oxygen concentration and heating rate on the characteristics of coal spontaneous comoustion. *J. Safety Environ.* **2023**, *23* (1), 43−48.
(54) Chen, X. K.; Yi, X.; Deng, J. Experiment study of characteristic self-heating intensity of coal. *J. China Coal Soc.* **2005**, No. 5, 81−84.
(55) Kalianjin, N. B. Spontaneous combustion of coal and its prediction. Fire prevention and extinguishing technology in Coal seam (Volume 1). *Translated by Ministry of Coal Industry Sci. Technol. Info.* **1984**, 132−147.
(56) Zhang, J. W.; Choi, W. Y.; Ito, T.; Takahashi, K.; Fujita, M. Modelling and parametric investigations on spontaneous heating in coal pile. *Fuel* **2016**, *176*, 181−189.
(57) Zhang, H. M.; Zhang, X. M.; Wang, Y. J.; Dong, W.; Fan, J. F.; Sasaki, K. Application of aging effect model in numerical simulation for predicting spontaneous combustion of coal stockpiles. *J. Therm. Anal. Calorim.* **2022**, *147* (23), 13847−13860.
(58) Zheng, Y. N.; Li, Q. Z.; Zhu, P. F.; Li, X. W.; Zhang, G. Y.; Ma, X.; Zhao, Y. Study on Multi-field Evolution and Influencing Factors of Coal Spontaneous Combustion in Goaf. *Combust. Sci. Technol.* **2023**, *195* (2), 247−264.
(59) Xu, Y.; Li, Z. J.; Liu, H. S.; Zhai, X. W.; Li, R. R.; Song, P. F.; Jia, M. T. A model for assessing the compound risk represented by spontaneous coal combustion and methane emission in a gob. *Journal of Cleaner Production* **2020**, *273*, No. 122925.
(60) Shi, X. Q.; Zhang, C. B.; Jin, P. G.; Zhang, Y. T.; Jiao, F. Y.; Xu, S. Y.; Cao, W. G. Eliminating scale effect: Development and attenuation of coal spontaneous combustion. *Fuel* **2024**, *357*, No. 130073.
(61) Wang, Z. H.; Liu, S.; Liu, P. Development of underground spontaneous combustion prediction and monitoring system. *Mining Safety Environ. Protect.* **2006**, No. 02, 12−89.
(62) Chen, X. K.; Deng, J.; Wen, H.; Wang, W. F.; Zheng, X. Z.; Wu, J. B.; Xu, C. L.; Cheng, F. M. *Mine Wireless Ad Hoc Network Temperature Measuring Device*; Xi 'an University of Science and Technology: Xi'an, 2009.
(63) Wang, W. F. *Development and Research on Remote Monitoring System of Borehole Temperature in Coalfield Fire Wireless Ad Hoc Network*; Xi 'an University of Science and Technology: Xi'an, 2010.
(64) Liu, Q. *Research of Wireless Ad-hoc Temperature Measurement System Used in Goaf Based on ZigBee*; Xi'an University of Science and Technology: Xi'an, 2012.
(65) Su, D. B. Present Status of Development of Optical Fibre Temperature Sensor. *Transducer and Microsystem Technologies* **1995**, *6*, 1−6.
(66) Li, Q.; Wang, Y. S.; Liu, X. M. Application situation of temperature monitoring of optic fiber sensor in power system. *Power System Protection and Control* **2010**, *38* (01), 135−140.
(67) Hang, H. Y.; Zhu, X. Y. The Application of Fiber Distributed Temperature Measurement System in Coal Mine Fire Warning. *Sci-tech Innovation and Productivity* **2007**, No. 10, 91−92.
(68) Yu, Q. Application of Distributed Fiber Temperature Measurement Technology in Coal Mine. *Journal of Mine Automation* **2012**, *38* (4), 5−8.
(69) Xie, J. W.; Lu, J.; Shang, G. K. F.; Yang, S. J.; Fan, Z. D.; Xing, Z. Application of Distributed Optical Fiber Temperature Detection Technology in Spontaneous Combustion Monitoring of Large Angle Flammable Coal Seam Goaf. *Safety in Coal Mines* **2014**, *45* (11), 118−121.
(70) Bai, Y. Q. Application of distributed optical fiber temperature measurement system in monitoring spontaneous combustion of coal in goaf. *Coal Mine Modernization* **2013**, No. 05, 85−89.
(71) Wen, H.; Wu, K.; Ma, L.; Wang, W. F.; Wang, T. Application of Distributed Optical Fiber Temperature Measurement System in Monitoring Goaf Coal Spontaneous Combustion. *Safety in Coal Mines* **2014**, *45* (05), 100−105.
(72) Deng, J.; Wang, W. F.; Ma, L. Distributed optical fiber monitoring and early warning system for goaf temperature field. *Xi'an University of Science and Technology* **2013**, *45* (05), 100−105.
(73) Zhu, H. Q.; Wang, H. Y.; Wang, F. R.; Yang, C. T. Research Progress on Coal Stockpile Temperature Measuring Technology. *Coal Sci. Technol.* **2014**, *42* (1), 50−54.
(74) Li, J. *Study on Wireless Monitoring and Early Warning Technology of Coal Spontaneous Combustion in Qinglong Coal Mine*; Xi'an University of Science and Technology: Xi'an, 2020.
(75) Zheng, X. *Technology of Monitoring and Controlling on Spontaneous Combustion in Adjacent Goaf of Nantun Coal Mine*; Xi'an University of Science and Technology: Xi'an, 2017.
(76) Rodionov, V.; Tursenev, S.; Skripnik, I.; Ksenofontov, Y. Results of the study of kinetic parameters of spontaneous combustion of coal dust. *Journal of Minging Institute* **2021**, *246*, 617−622.
(77) Szurgacz, D.; Tutak, M.; Brodny, J.ła.; Sobik, L.; Zhironkina, O. The Method of Combating Coal Spontaneous Combustion Hazard in Goafs—A Case Study. *Energies* **2020**, *13* (17), 4538−4538.
(78) Uludag, S. A visit to the research on Wits-Ehac index and its relationship to inherent coal properties for Witbank Coalfied. *J. South Afr Inst Min Metall* **2007**, *107* (10), 671−679.
(79) Onifade, M.; Genc, B. A review of research on spontaneous combustion of coal. *International Journal of Mining Science and Technology* **2020**, *30* (3), 303−311.
(80) Chen, P.; Zhang, C.; Zhang, L.; Wang, X. Y. Progress and Prospects of Test Methods of Coal Spontaneous Combustion Tendentiousness. *Safety in Coal Mines* **2016**, *47* (3), 164−168.
(81) Deng, J.; Xu, J. C.; Zhang, Y. D.; Li, L. Experimental and numerical analysis of the shortest spontaneous ignition period of coal. *Journal of China Coal Society* **1999**, No. 3, 52−56.
(82) Liang, Y. T.; Song, S. L.; Lou, H. Z.; Lin, Q.; Feng, W. B.; Tian, F. C. An analytic solution of coal spontaneous combustion period calculation model. *Journal of China Coal Society* **2015**, *40* (9), 2110−2116.
(83) Huang, Z. A.; Ma, Z. Z.; Song, S. Y.; Yang, R.; Gao, Y. K.; Zhang, Y. H. Study on the influence of periodic weighting on the spontaneous combustion "three-zone" in a gob. *Journal of Loss Prevention in the Process Industries* **2018**, *55*, 480−491.
(84) Zhou, P. L.; Zhang, Y. H.; Huang, Z. A.; Yuan, F.; Gao, Y. K.; Wang, H.; Sun, Q. 4D dynamic simulation of coal oxidation heating law in gobs with heterogeneous porosity. *Chin. J. Eng.* **2016**, *38* (10), 1350−1358.
(85) Shao, L. S.; Li, X. C. Prediction of coal spontaneous combustion in caving zone with unbalanced data. *China Safety Sci. J.* **2017**, *27* (6), 61−66.
(86) Zhao, L. L.; Wen, G. F.; Shao, L. S. PCA-AdaBoost model for predicting coal spontaneous combustion in caving zone with imbalanced data. *China Safety Sci. J.* **2018**, *28* (3), 74−78.
(87) Lei, C. K.; Deng, J.; Cao, K.; Xiao, Y.; Ma, L.; Wang, W. F.; Ma, T.; Shu, C. M. A comparison of random forest and support vector machine approaches to predict coal spontaneous combustion in gob. *Fuel* **2019**, *239*, 297−311.
(88) Deng, J.; Lei, C. K.; Cao, K.; Ma, L.; Wang, C. P.; Zhai, X. W. Random forest method for predicting coal spontaneous combustion in gob. *J. China Coal Soc.* **2018**, *43* (10), 2800−2808.
(89) Deng, J.; Lei, C. K.; Cao, K.; Ma, L.; Wang, W. F. Support vector regression approach for predicting coal spontaneous combustion. *Journal of Xi'an University of Science and Technology* **2018**, *38* (02), 175−180.
(90) Yu, M. G.; Jia, H. L.; Hu, Z. X. *Mine Fire Prevention and Control*; National Defense Industry Press: Beijing, 2013: pp 11−13.
(91) Dai, G. L. Analysis on the optimization and use of coal spontaneous combustion index gas. *Coal Sci. Technol.* **1996**, No. 9, 44−47.
(92) Wu, C. L.; Wu, A. Y.; Cai, K. X. Experimental Study on Tendency of Coal Spontaneous Combustion Based on CO Concentration. *China Safety Sci. J.* **2006**, No. 10, 131−134.
(93) Xu, C. F.; Fu, G.; Zheng, Z. Y.; Yao, H. F.; Zhang, Q. Experimental study on the spontaneous combustion index gas optimization of 3−1 coal seam in Nalin River No.2 mine. *J. Safety Environ.* **2014**, *14* (3), 118−122.

(94) Deng, J.; Li, B.; Li, Z. B.; Zhang, Y.; Guang, X. J. Experiment Study on Gas Indexes Optimization for Coal Spontaneous Combustion Prediction. *Coal Sci. Technol.* **2014**, *42* (1), 55−79.
(95) Liang, Y. T.; Zhang, J.; Wang, L. C.; Luo, H.; Ren, T. Forecasting spontaneous combustion of coal in underground coal mines by index gases: A review. *Journal of Loss Prevention in the Process Industries* **2019**, *57*, 208−222.
(96) Luo, H. Z.; Liang, Y. T. Current Status and Perspective of Forecast and Prediction Techniques for Spontaneous Combustion of Coal. *China Safety Sci. J.* **2003**, No. 3, 79−81.
(97) Deng, J.; Li, B.; Li, Z. B.; Zhang, Y.; Guan, X. J. Experiment Study on Gas Indexes Optimization for Coal Spontaneous Combustion Prediction. *Coal Sci. Technol.* **2014**, *42* (1), 55−79.
(98) Wang, F. S.; Wang, J.; Gu, L.; Liu, C.; Wang, C. Study on multi-parameter index system for prediction and forecast of coal spontaneous combustion. *J. Safety Sci. Technol.* **2018**, *14* (6), 45−51.
(99) Guo, J.; Wen, H.; Zheng, X. Z.; Liu, Y.; Cheng, X. J. A method for evaluating the spontaneous combustion of coal by monitoring various gases. *Process Safety and Environmental Protection* **2019**, *126*, 223−231.
(100) Ma, L.; Zou, L.; Ren, L.-F.; Chung, Y.-H.; Zhang, P.-Y.; Shu, C.-M. Prediction indices and limiting parameters of coal spontaneous combustion in the Huainan mining area in China. *Fuel* **2020**, *264*, No. 116883.
(101) Ye, Z. L. Study on early warning platform of turned over combustion based on oxidation and temperature rising law of coal pile. *Coal Sci. Technol.* **2018**, *46* (11), 82−87.
(102) Tan, B.; Shao, Z. Z.; Guo, Y.; Zhao, T.; Zhu, H. Q.; Li, C. X. Research on grading and early warning of coal spontaneous combustion based on correlation analysis of index gas. *China Safety Sci. J.* **2021**, *31* (2), 33−39.
(103) Ren, W. X.; Guo, Q.; Shi, J. T.; Lu, W.; Sun, Y. Construction of early warning indicators for coal spontaneous combustion based on statistical characteristics of index gases. *J. China Coal Soc.* **2021**, *46* (6), 1747−1758.
(104) Wen, H.; Liu, Y.; Guo, J.; Jin, Y.; Zheng, X. Z. A multi-index-classified early warning method for spontaneous combustion of coal under air leakage blocking. *International Journal of Oil, Gas and Coal Technology* **2021**, *27* (2), 208−226.
(105) Wen, H.; Liu, W. Y.; Zheng, X. Z.; Guo, J.; Fei, J. B.; Wu, J. B. *Research on Grading Early Warning and Active Prevention and Control Technology of Coal Spontaneous Combustion*; Xi'an University of Science and Technology: Xi'an, 2018.
(106) Guo, J.; Wang, K. X.; Jin, Y.; Wen, H.; Wu, J. B.; Cai, G. B. Fine division method of coal spontaneous combustion process and its intelligent monitoring and early warning: Technological change in precise prevention and control of coal fires. *J. China Coal Soc.* **2023**, *48* (S1), 111−121.
(107) Deng, J.; Wang, W. F.; Cheng, X. K.; Jing, X. P. Research of Monitoring and Control System of Wireless Temperature Sensor Ad-hoc Networks for Coal Spontaneous Combustion Based on CC1020. *J. Mine Automation* **2009**, *35* (06), 8−11.
(108) Zhang, J.; Kuenzer, C. Thermal surface characteristics of coal fires results of in-situ measurements. *Journal of Applied Geophysics* **2007**, *63* (3), 117−134.
(109) Zhang, X.; Zhang, J.; Kuenzer, C.; Voigt, S.; Wagner, W. Capability evaluation of 3 ∼ 5 μm and 8 ∼ 12.5μm airborne thermal data for underground coal fire detection. *Int. J. Remote Sensing* **2004**, *25* (12), 2245−2258.
(110) Gao, C. K. *The Research and Application of Integrated Geophysical Methods on Accumulation Body*; Central South University: Chang Sha, 2009.
(111) Tang, J. R.; Cui, X. L.; Shi, J. F. New progress in the study of non-traditional geochemical exploration methods. *Geol. Bull. China* **2009**, *28* (2), 233−244.
(112) Hong, X. P.; Liang, H. D.; Lv, S.; Jia, Y. R.; Zhao, T. C.; Liang, W. L. Mercury emissions from dynamic monitoring holes of underground coal fires in the Wuda Coalfield, Inner Mongolia. China. *International Journal of Coal Geology* **2017**, *181*, 78−86.
(113) Guo, J.; Liu, H.; Jin, Y.; Cai, G. B.; Liu, Y.; Yang, P. P. Summary of underground hidden coal spontaneous combustion fire source detection methods and prospect of new technologies. *China Safety Sci. J.* **2022**, *32* (8), 111−119.
(114) Guo, J.; Wang, K. X.; Cai, G. B.; Jin, Y.; Liu, Y. Research progress of acoustic emission signal and its application prospect in coal temperature sensing field. *Coal Sci. Technol.* **2022**, *50* (11), 84−92.
(115) Guo, J.; Shang, H.; Cai, G.; Jin, Y.; Wang, K.; Li, S. Early detection of coal spontaneous combustion by complex acoustic waves in a concealed fire source. *ACS Omega* **2023**, *8* (19), 16519−16531.
(116) Deng, J.; Qu, G. Y.; Ren, S. J.; Wang, C. P.; Wang, J. R.; Zhao, X. Y.; Bai, G. X. Experimental study on acoustic wave propagation characteristics and main paths in loose coal. *J. China Coal Soc.* **2023**, *48* (3), 1238−1245.
(117) Guo, J.; Gao, W. J.; Cai, G. B.; Liu, Y., Wang, K. X. *Acoustic Temperature Measurement of Loose Coals Based on Pseudo-Random Sequences and Application Research*; Coal Science and Technology, 2023, pp 1−9.
(118) Deng, J.; Qu, G. Y.; Ren, S. J.; Wang, C. P.; Zhao, X. Y. Experimental study on optimization of low frequency acoustic transmission frequency in loose coal. *Safety Coal Mines* **2022**, *53* (1), 15−23.
(119) Yang, G.; Yan, J. D.; Shen, G. Q.; An, L. S.; Li, Z. J. Real time monitoring of accumulated pulverized coal temperature field based on acoustic method. *Clean Coal Technol.* **2022**, *28* (4), 59−65.
(120) Guo, M. *Temperature Measurement of Stored Bioma ss Using Acoustic Method*; North China Electric Power University: Beijing, 2019.
(121) Guo, J.; Chen, C. M.; Jin, Y. F.; Cai, G. B.; Wen, H.; Li, S. Study on the mapping model of sound velocity and coal temperature for quasi-porous media in loose coal. *J. China Coal Soc.* **2023**, 1−13.
(122) Wu, J. J.; Jiang, W. G.; Liu, X. C.; Gu, L.; Li, J. H. Innovative technologies for exploration, monitoring and extinction of underground coal fires. *J. China Coal Soc.* **2009**, *34* (12), 1669−1674.
(123) Zhou, B.; Zhou, W. Q.; Dong, Z. Y.; Wang, J. F. Experimental study on radon exhalation characteristics of coal and rock during oxidation and heating. *J. China Coal Soc.* **2020**, *45* (S2), 859−866.
(124) Zhu, H. Q.; Yuan, J.; Zhuo, J. L.; Zhu, X. M. Research on the Status of Underground Coal Fire Distribution and Development of the Detection Technology. *Ind. Saf. Environ. Prot.* **2019**, *45* (12), 28−32.
(125) Wen, H.; Cheng, X. J.; Xu, Y. H.; Ma, L.; Guo, J.; Jing, X. Y.; Wang, B. Q.; Jian, J. C. Law of radon precipitation and migration in loose coal during spontaneous combustion process. *J. China Coal Soc.* **2019**, *44* (9), 2816−2823.
(126) Zhao, X. X.; Zhang, P. Research review on detection methods of coal spontaneous combustion high temperature region in mine. *Energy Technol. Manag.* **2016**, *41* (3), 26−28.
(127) Jin, Y. F.; Deng, J.; Xu, Y. H.; Sun, H. H. Application of radon detection method in detecting of underground coal fire. *J. Xi'an Univ. Sci. Technol.* **2010**, *30* (6), 647−650.
(128) Wang, Z. P.; Cheng, W. M.; Xing, S.; Song, X. M.; Su, S. G. The calculation of close-range coal inflammation position at coal-roads based on infrared detecting and inverse heat conduction technology. *J. China Coal Soc.* **2003**, No. 6, 603−607.
(129) Li, Q.-W.; Xiao, Y.; Zhong, K.-Q.; Shu, C.-M.; Lu, H.-F.; Deng, J.; Wu, S. Overview of commonly used materials for coal spontaneous combustion prevention. *Fuel* **2020**, *275*, No. 117981.
(130) Ou, S. N.; Liu, J. G.; Jin, L. Z.; Sun, Z. C. Inhibition effect of CO and N_2 on the explosion and spontaneous combustion performance of silo mixed coal. *J. China Univ. Mining Technol.* **2020**, *49* (2), 387−394.
(131) Deng, J.; Xi, H. J.; Zhai, X. W.; Zhang, Y. N. Key parameters of liquid CO_2 perfusion for fire control in coal mine goaf. *J. Xi'an Univ. Sci. Technol.* **2017**, *37* (5), 605−609.
(132) Yu, M.; Yang, N.; Liu, Z.; Li, H.; Wang, L.; Wu, M.; Li, J.; Yu, Y. Experimental preparation and mechanism analysis of a neotype

composite gel for coal spontaneous combustion prevention and coal-fire extinguishment. *Fuel* **2023**, *339*, 127448.

(133) Deng, J.; Bai, Z. J.; Xiao, Y.; Song, Z. Y. Present Situation and Challenge of Coal Spontaneous Combustion Disasters Prevention and Control Technology. *Safety Coal Mines* **2020**, *51* (10), 118−125.

(134) Cui, C. B.; Jiang, S. G.; Shao, H.; Zhang, W. Q.; Wang, K.; Wu, Z. Y. Experimental study on thermo-responsive inhibitors inhibiting coal spontaneous combustion. *Fuel Process. Technol.* **2018**, *175*, 113−122.

(135) Bai, Z. M. *Study on Microencapsulated Compound Inhibitor for Preventing Coal Spontaneous Combustion*; China University of Mining and Technology: Xuzhou, 2019.

(136) SHI, Q. L.; Qin, B. T. Experimental research on gel stabilized foam designed to prevent and control spontaneous combustion of coal. *Fuel* **2019**, *254*, No. 115558.

(137) Lu, Y. *Study on the Inorganic Solidified Foam and its Characteristics for Preventing and Controlling Spontaneous Combustion of Coal*; China University of Mining and Technology: Xuzhou, 2015.

(138) Tang, Y. B. Inhibition of low-temperature oxidation of bituminous coal using a novel phase-transition aerosol. *Energy Fuels* **2016**, *30* (11), 9303−9309.

(139) Li, B.; Deng, J.; Xiao, Y.; Zhai, X. W.; Shu, C. M.; Gao, W. Heat transfer capacity of heat pipes: An application in coalfield wildfire in China. *Heat and Mass Transfer* **2018**, *54*, 1755−1766.

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