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REVIEW

Combustion mechanism and control approaches of underground coal fires: a review

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Abstract

With the large-scale mining of coal resources, the huge economic losses and environmental problems caused by underground coal fires have become increasingly prominent, and the research on the status quo and response strategies of underground coal fires is of great significance to accelerate the green prevention and control of coal fires, energy conservation and emission reduction. In this paper, we summarized and sorted out the research status of underground coal fires, focused on the theoretical and technical issues such as underground coal fire combustion mechanism, multiphysics coupling effect of coal fire combustion, fire prevention and extinguishing technology for underground coal fires, and beneficial utilization technology, and described the latest research progress of the prevention and control for underground coal fire hazards. Finally, the key research problems in the field of underground coal fire hazards prevention and control were proposed in the direction of the basic theory, technology research, comprehensive management and utilization, with a view to providing ideas and solutions for the management of underground coal fires.

Keywords Underground coal fire · Combustion mechanism · Multiphysics coupling effect · Disaster prevention and control · Turning harm into benefit · Response strategy

1 Introduction

The exploitation and utilization of mineral resources is the basis for the progress of human civilization, and underground mining is the principal pathway for human beings to obtain resources and energy. Coal, as the basic energy in China, plays a cornerstone role in developing the national economy and ensuring energy security, occupying a significant strategic position. Coal accounts for about 90% of the proven fossil energy reserves in China, and such energy endowment fully reflects its strong capacity of a stable economy and independent guarantee, which also fundamentally determines that coal as the main energy structure is irreplaceable in the short term (Zou et al. 2016; Ju et al. 2019).

With the growing importance of green and low-carbon concepts globally, countries around the world have made commitments related to carbon emissions. China also commits to peak carbon dioxide emissions before 2030 and achieve carbon neutrality before 2060 (Xi 2020), which is a reflection of China's responsibility as a major country in addressing global climate change and means that China's energy development has reached a critical period of transformation and change. This move poses a new challenge to the coal industry with high consumption, high carbon and high pollution, and also brings an important juncture for industry transformation. Under the carbon peaking and carbon neutrality goals, it is urgent to develop and utilize coal resources in a green, low-carbon, clean and efficient way, and promote the implementation of carbon reduction actions in the coal industry.

Underground coal fires, uncontrollable combustion that occurs in underground coal seams with certain environmental impacts, are a global persistent ecological hazard that occurs widely in China, India, the United States, and Australia (Stracher and Taylor 2004; Pone et al. 2007; Wu and Liu 2011). Large coal fires are concentrated in the main coal-producing regions of Xinjiang, Inner Mongolia, Shanxi

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and Ningxia in China (Zhang et al. 2008; Song and Kuenzer 2014). As shown in Fig. 1, coal fires cause immeasurable coal mining stagnation and resource wastage (Zhang and Kuenzer 2007; Zhang et al. 2007), and release toxic and harmful gases (CO, SO_2, H_2S, N_2O, NO_x) that induce pollution problems such as haze and acid rain, which seriously threaten the life and health of species (Voigt et al. 2004; O'Keefe et al. 2010). Sulfur and coal tar and other substances formed by combustion deteriorate the physical and chemical properties of soil, pollute groundwater, and create unstable surface structures, fissures, and subsidence that pose safety hazards to surface facilities (Zhang et al. 2004; Tang 2019). Moreover, the large amount of carbon dioxide released from coal fires and the resulting destruction of vegetation are in serious contradiction to the green and low-carbon development requirements under the carbon peaking and carbon neutrality goals. Coal fires have become a serious threat to adjustments of the national energy structure, strategic deployment of carbon peaking and carbon neutrality goals and green and sustainable development of the ecological environment. According to the data, China loses hundreds of millions of tons of coal resources each year due to coal fires, and the direct economic loss exceeds 20 billion CNY (Song and Kuenzer 2014). The annual carbon dioxide emissions caused by coal fires exceed 500,000 tons (Song 2015), accounting for about 2% of global fossil fuel carbon emissions (Shi et al. 2017), which is equivalent to the carbon dioxide absorption of a 10,000 square meter area of forest for about 90 years. Therefore, understanding the development status of underground coal fires and exploring their prevention and response strategies are important elements for energy conservation and emission reduction, protecting coal resources and the ecological environment, which is a major step to help the successful transformation of China's coal industry.

In this paper, we sorted out the current research status of underground coal fires through a large amount of literature, expounded the combustion mechanism of underground coal fires under the coupling effect of multiple fields, summarized the current fire prevention and extinguishing technology for underground coal fires and the application of the idea of "turning harm into benefit", and looked forward to the development trend of underground coal fire prevention and control, with a view to providing ideas and strategies to deal with the global disaster of underground coal fires.

2 Statistics of research literature related to underground coal fires

In order to fully understand the status quo of underground coal fires in China, the development of prevention and control technologies and the influence of scientific research in the world, we searched the literature related to underground coal fires in the Web of Science (WOS), Engineering Index (EI), and China National Knowledge Infrastructure (CNKI) databases until 2022 by using underground coal fire and coalfield fire as search terms in Chinese and English. The trend of the quantity of literature related to underground coal fires in the past 50 years is given in Fig. 2. The figure

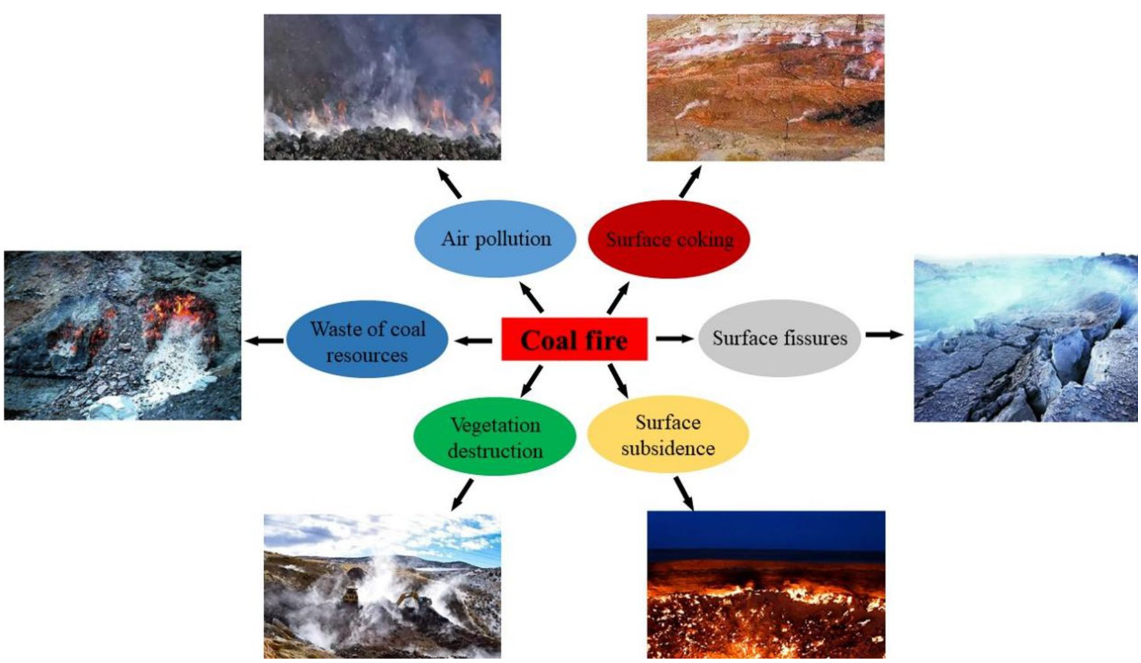


Fig. 1 Diagram of coal fire hazard

displays that the quantity of literature related to underground coal fires began to increase continuously from 2000, and especially after 2010, the quantity of literature tends to increase more significantly. It indicates that underground coal fires are receiving more and more attention and the research fever is rapidly increasing along with the exploration of large-scale development of underground coal resources and the increasing attention to environmental issues.

Both Web of Science and The Engineering Index databases show that the quantity of literature related to underground coal fires in China accounts for one-third or even up to half of all related literature, as shown in Fig. 3. It indicates that our research on subsurface coal fires has occupied an important position in the related research work of the world.

According to the statistics of literature related to underground coal fires in China National Knowledge Infrastructure (CNKI) database, the hot research topics in the field of coal fires in China mainly include: coal fire detection technology, combustion mechanism, monitoring and early warning technology, fire prevention and extinguishing technology, coal fire distribution, comprehensive management of fire zones, coal fire evaluation, and coal fire utilization (Fig. 4). These research hotspots are mainly related to the evolution law of underground coal fires, fire zone detection and monitoring technology, and comprehensive coal fire management means. The detection and monitoring technology of underground coal fires involves such methods as radon detection, magnetic detection, and remote sensing detection, centering on the difficult problem of determining the burning center, depth and range of coal fire zones. The occurrence mechanism, multiphysics coupling effect and spatial characteristics of coal fires have been a worldwide problem in the field of coal spontaneous combustion and occupy a significant research position due to the complexity of coal properties and coal fire occurred conditions. Prevention and extinguishing technology of underground coal fires is constantly updated as fire prevention materials evolve, which is also a hot issue in the research of coal fires. Furthermore, the research on coal fire utilization has gradually become a new research hotspot under the impact of "turning harm into benefit" and green and low-carbon development trend of the mining industry in recent years.

Combined with the research hotspots of underground coal fires, after analysis and comparison, it is found that many papers have comprehensively summarized detection and monitoring of coal fires in the past. Therefore, under the background of mining-induced underground coal fire hazards, the following four elaborates on the combustion mechanism of underground coal fires, multiphysics coupling in the combustion affected area of coal seams, prevention and extinguishing technology of underground coal fires, and the innovative use of beneficial utilization technology of underground coal fires have been mainly conducted.

3 Combustion mechanism of underground coal fires

Underground coal fires can be divided into two types of coal seam outcrop fires and mining-induced fires owing to the difference in the environment they are located (Wang 2014b). The combustion area will be covered by disturbed rock strata, and coal seam outcrop fires will change to mining-induced coal fires as coal seam combustion continues to occur and extends underground (Wang et al. 2016). Coupled with the large-scale mining of coal resources, mining-induced underground coal fires have undoubtedly become the main type of underground coal fire hazard. As a result,

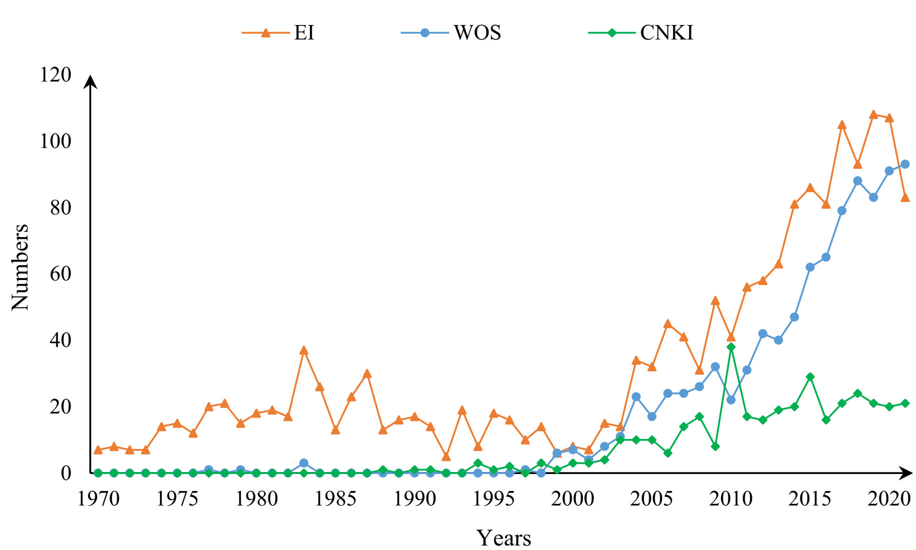
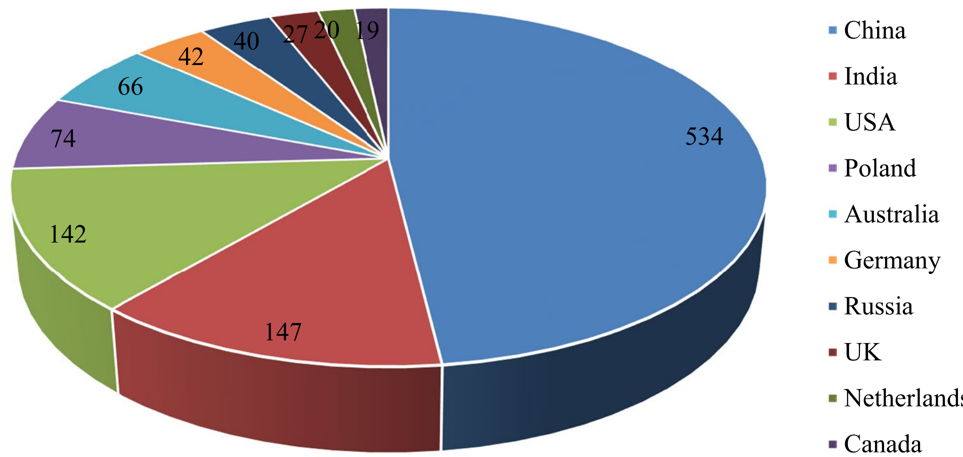


Fig. 2 Year-by-year change in the literature related to underground coal fires



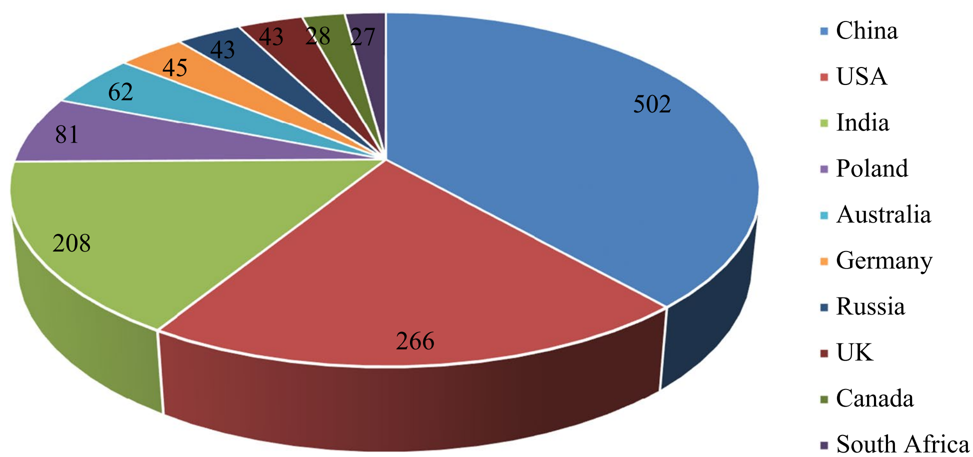


Fig. 3 Quantity of published literature related to underground coal fires in different countries

this paper focuses on mining-induced underground coal fires.

The underground coal fire is also a special kind of combustion phenomenon. The combustion of combustible materials is determined by the three elements of "ignition source, combustible material, and oxidizer". The occurrence of underground coal fires also requires the three elements shown in Fig. 5, i.e., coal with a tendency for spontaneous combustion, a certain concentration of oxygen, and a temperature reaching the spontaneous combustion point of coal (Onifade and Genc 2019; Aich et al. 2021). The semi-enclosed space formed by the effect of mining also creates conditions for the occurrence of coal fires. The research methods for the action mechanism of each elements in the process of coal spontaneous combustion include thermal analysis techniques such as cross-point temperature (CPT/XPT), isothermal heating, adiabatic self-heating, constant temperature difference (CTD), differential thermal analysis (DTA) and differential scanning calorimetry (DSC), as well as material analysis techniques, which include Fourier transform infrared spectroscopy (FTIR), electron spin resonance (ESR), X-ray diffraction (XRD) and so on. The research principles and obtained parameters of the above methods are shown in Table 1.

3.1 Spontaneous combustion tendency of coal

As shown in Fig. 5, coal is a porous material with many active structures on its surface, which can continuously adsorb oxygen molecules from the air and give off gaseous products and heat (Basu et al. 2019). It accumulates heat and heats up under certain conditions, which leads to

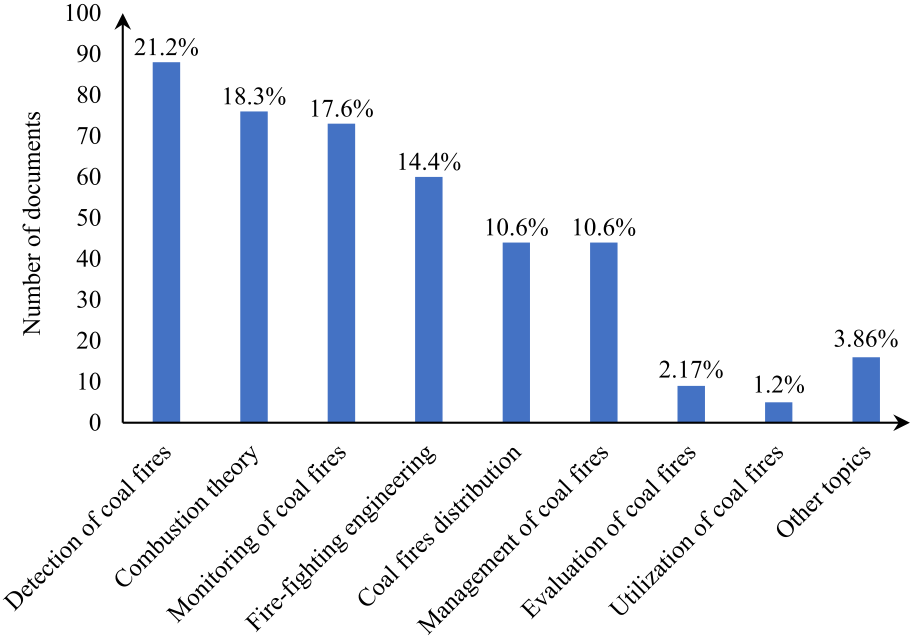


Fig. 4 Main research topics shown in the literature related to underground coal fires in China National Knowledge Infrastructure database

spontaneous combustion of coal after reaching a certain temperature. Studies on the mechanism of spontaneous combustion of coal have been conducted for more than a century, and early scholars put forward the hypothesis of spontaneous combustion of coal from a different perspective. Allardice and Xu (Allardice 1966; Xu et al. 2000a, b) were concerned with the adsorption of oxygen by coal, which contributed to the development of the theory of coal-oxygen recombination. Some scholars paid attention to the molecular structure of coal. For example, Li (1996) believed that free radicals generated in the process of molecular cracking of coal promoted the oxidation and spontaneous combustion of coal, and proposed the hypothesis of free radical interaction. Lopez et al. (1998) focused on the movement of hydrogen atoms among coal molecules and developed the hydrogen atom interaction assumption. Wang et al. (1999) simulated the interaction between the tree-like structure of pores in coal and oxygen, and proposed the group interaction hypothesis. The above assumptions have elaborated the mechanism of coal spontaneous combustion from the microscopic point

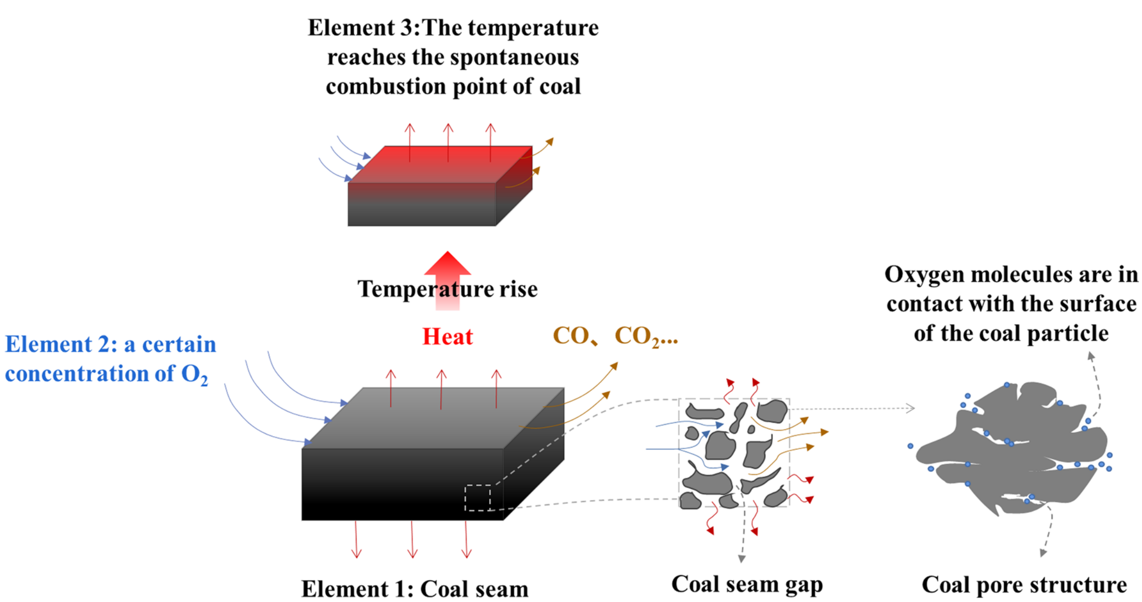


Fig. 5 Diagram of the three elements for the occurrence of underground coal fires

Table 1 Methods, obtained parameters and principles for studying on coal spontaneous combustion mechanism

Methods		Obtained parameters	Principle
Thermal analysis techniques	CPT/XPT	Crossing-point temperature and heating rate of coal (Saffari et al. 2019)	Use different external heating methods to obtain dynamic parameters of coal spontaneous combustion
	Isothermal heating	Gas products (Czerski et al. 2019)	
	Adiabatic self-heating	Kinetic abrupt change temperature of coal (Zhu et al. 2014)	
	CTD	Kinetic abrupt change temperature of coal (Yong et al. 2019)	
	DTA	Variation of coal oxidation characteristics with temperature (Zhang et al. 2016)	
	DSC	The relationship between heat flow and temperature (Deng et al. 2018; Qu et al. 2019)	
Material analysis techniques	FTIR	Functional group changes of coal (Zhou et al. 2017a, b, c, d)	Analyze the changes of structure and elements in the process of chemical change of materials
	ESR	Changes in the chemical structure of coal (Song et al. 2018)	
	XRD	Changes in the chemical structure of coal (Shi et al. 2018)	

of view, but they all have certain limitations and fail to fully reveal the mechanism of coal spontaneous combustion. To date, many scholars have studied the spontaneous combustion tendency through a large number of experiments to reveal the role of the nature of coal itself on the process of coal spontaneous combustion based on the theory of coal-oxygen complex interaction.

The spontaneous combustion tendency is closely related to the microstructure of coal. The size and pore structure of coal particles, the water content of coal and the elements contained, and the active functional groups all have an effect on the coal-oxygen complex reaction (Zhao et al. 2019a, 2022; Zhang et al. 2022; Song et al. 2021). Some scholars have studied the spontaneous combustion characteristics of coal through thermodynamic experiments (Qin et al. 2012; Zhao et al. 2019b). The particle size and porosity of coal affect its specific surface area, and the larger the specific surface area, the better the reaction area and heat transfer effect in contact with oxygen, and this conclusion has been confirmed by relevant scholars. Qin et al. (2012) tested the oxygen consumption rate of coal samples with different particle sizes by heating and oxidation experiments, so as to calculate the oxygen consumption rate of residual coal in the mined-out area, and established a mixed particle size oxygen consumption rate equation considering temperature, particle size, and oxygen concentration and verified its accuracy. Saffari et al. (2019) and Song et al. (2018) investigated the effect of water content and pyrite on coal oxidation. Saffari et al. (2019) studied the effects of pyrite and moisture content on coal oxidation using CPT and R70 test methods. The results indicated that: pyrite can catalyze the oxidation reaction; 20% moisture content is the critical value that affects the spontaneous combustion rate of coal, beyond which the spontaneous combustion rate decreases. Song et al. (2018) investigated the effect of water leaching on the coal structure and oxidation using ESR and other instruments, and found that the porosity and free radical content of coal increase after water leaching, which is conducive to the migration and contact reaction of oxygen molecules between pores. Other scholars investigated the changes of coal molecular structure in the oxidation reaction, and found that the active functional groups in coal molecules can be converted to free radicals during the reaction, and the free radicals are more likely to react with oxygen exothermically (Zhou et al. 2021). Zhu et al. (2014) analyzed the relationship between the apparent activation energy of coal and the degree of coal metamorphism by adiabatic oxidation experiments, and analyzed the controllability of spontaneous combustion of coal with different degrees of metamorphism by the measured kinetic abrupt change temperature (Tc). Zhou et al. (2017a) measured the functional group changes of three coal samples below 230° by TG-FTIR technique. The TG curves were obtained by measuring the mass changes of coal in real time, and the results showed that the changes of methyl and methylene groups are linearly related to the mass changes of coal.

3.2 Low-temperature oxidation of coal

Oxygen is one of the essential elements for coal spontaneous combustion, and the way for fresh air to enter the underground coal seam mainly includes the fractures in overlying rock strata and the ventilation tunnel. The different flow rate of air and the different oxygen content of air will affect the coal oxidation process. Deng et al. (2018) analyzed the effect of different oxygen concentrations on the kinetic parameters of coal oxygen reaction by DSC method, and found that higher oxygen concentration could increase the number of active functional groups in coal molecules and decrease the apparent activation energy. Su et al. (2017) conducted low-temperature coal oxidation experiments in the range of oxygen concentrations from 6% to 21%, and found that oxygen concentration has little effect on the oxidation reaction at temperatures above 80 °C. Wang et al. (2022) investigated the effect of oxygen concentration and ventilation on the high temperature zone and found that the air supply is proportional to the change of high temperature point in the mined-out area, while the oxygen volume fraction is a key factor in determining whether the coal would spontaneously combust. Wieckowski et al. (2020) studied the concentration changes of ethane, ethylene and other gaseous products during the heating and cooling stages of coal samples under different flow rates of synthesis air and nitrogen, and found that the temperature change and airflow rate have an effect on the CO/CO_2 index of the generated gas. In addition, the fracture development status of overlying rock strata also affects the oxygen distribution and gas flow mode in the coal seam, and then affects the coal oxidation reaction. Wang et al. (2016) proposed a series of distribution models of void rate in the disturbed strata above the goaf of coal seam and conducted numerical simulation of the combustion law in the goaf. The results showed that the void rate distribution determines the form of the flow field, and the gas flow velocity is high in the area where the void rate is large. Scholars have studied the influence of the advancing speed of the working face and the ventilation mode on underground coal fires during mining. Wang et al. (2022) studied the effect of the advancing speed of the working face on the high temperature area, and found that the advancing speed is negatively correlated with the size of the high temperature point, and the faster the speed, the more the high temperature area shifts to the deeper part; in addition, as the working face advances, the oxygen concentration in the deeper mined-out area farther away from the working face becomes smaller.

3.3 Effect of temperature on coal oxidation

In order to discuss the effect of temperature on coal oxidation reaction, it is necessary to clarify how the temperature rises. The current studies have shown that the main pathway of heat generation in the self-heating process of underground coal seams is the exotherm of coal oxidation, and the reaction mechanism of coal oxidation exothermic has been proved by many studies. Xu (2017) experimentally verified that the main pathway of heat generation in the early low-temperature oxidation stage of coal is the exotherm of decomposition of oxygen-containing functional groups. Qu et al. (2019) revealed by DSC analysis that adsorbed water can catalyze the generation of free radicals in coal molecules, thus accelerating the exothermic coal oxygen reaction. In addition, it has also been suggested that the water content and pyrite in coal seams can also affect exothermic oxidation reactions. Beamish and Theiler (2019) believed that dehumidification of coal samples and water evaporation could lead to heat loss; on the contrary, pyrite can use water for oxidation reactions and generate heat under certain conditions, reducing the heat loss from water evaporation. The heat generated by the above different pathways accumulates under certain conditions and heats the coal body continuously until spontaneous combustion occurs.

The coal oxidation reaction increases the ambient temperature, which in turn affects the coal oxidation reaction rate. Studies have been conducted mainly to investigate the effects of temperature on both the movement intensity of gas molecules and the surface active structure of coal. On the one hand, as the coal oxidation reaction gives off heat in the semi-enclosed space, the heat is transferred to the surrounding environment by heat conduction and heat convection, which increases the ambient temperature. Under this circumstance, the average kinetic energy of gas molecules increases, the diffusion ability and permeability are subsequently enhanced, and the contact chance between oxygen molecules and coal increases, which promotes the continuation of the reaction. Wang et al. (Wang et al. 2017) determined the relationship between the change of coal sample temperature and the change of cover surface temperature and CO content, and the results showed that the oxidation reaction rate increases with the increase of coal sample temperature, and 80 °C is used as the critical temperature for the rapid oxidation stage of the test coal sample. This study laterally reflects that the movement intensity of gas molecules increases with increasing temperature. Peng et al. (Peng et al. 2017) investigated the effect of high temperature on gas flow within the heat accumulation zone of the mined-out area, and the numerical simulation results showed that the temperature difference caused by the high temperature heat source can cause the change of surrounding gas flow rate. On the other hand, the increase in temperature will increase the number and activity of active structures on the coal surface and enhance the ability to bind to oxygen molecules. Zhang et al. (2018) proposed the DSCIP method to determine the temperature of coal spontaneous combustion by TG/DSC analysis, ESR technique and mathematical modeling, and found that the faster the temperature rises, the higher the spontaneous combustion temperature will be, and the conclusion was confirmed by the variation law of heat flux, free radicals and activation energy. Xu et al. analyzed the reaction characteristics of free radicals and functional groups by ESR and FTIR, and found that the concentration of free radicals increases in each rank of coal samples with the increase of temperature, while the variation law of oxygen-containing functional groups differ greatly with the coal rank.

4 Multiphysics coupling in the combustion affected area of coal seams

The occurrence and development of underground coal fires are jointly affected by gas concentration field, seepage field, temperature field, fracture field, etc. It is a thermodynamic disaster under the coupling effect of multiple fields. To date, many scholars have conducted qualitative analysis and quantitative research on the coupling of multiple fields in the combustion affected area of coal seams, which lays a theoretical foundation for the research of underground coal fire hazard mechanisms and fire prevention and extinguishing technology.

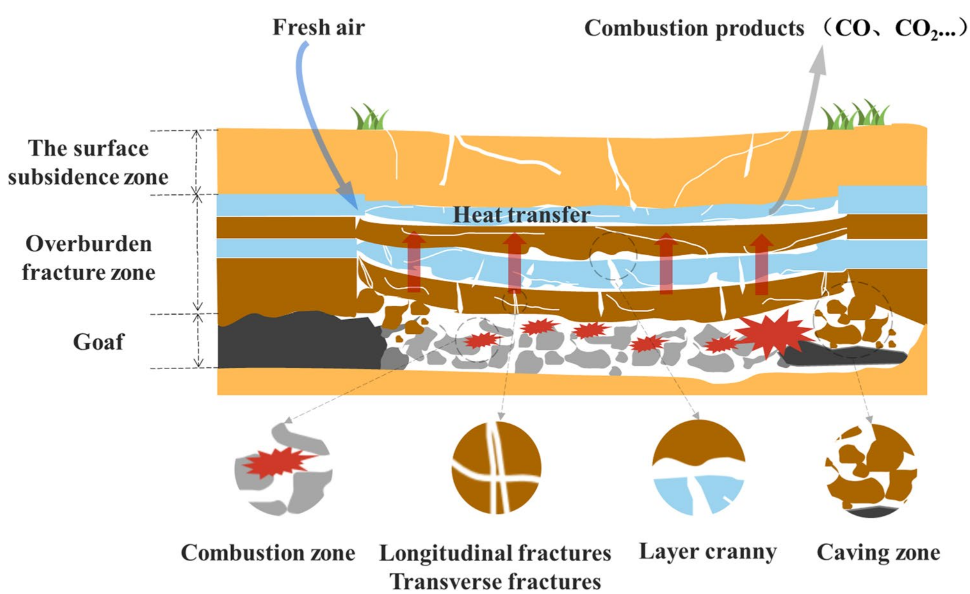
4.1 Multiphysics coupling mechanism

After coal mining, a goaf will appear in the coal seam. Fresh air will enter the mined-out area through the fissures of the overlying rock strata, and oxidizes with the residual coal in the mined-out area. Then spontaneous combustion will occur after a certain time of heating, forming an underground coal fire zone. The formation and development process of mining-induced underground coal fires is given in Fig. 6.

With the expansion of the mined-out area, the stress state around the goaf and the overlying rock mass changes, the overlying rock strata will bend, break and sink, and even the ground surface will rupture and collapse. In this process, many cracks, voids and other structures are generated in the goaf of seams and the overlying rock strata (Li et al. 2022). Its composition includes: pores formed by the collapse of the direct top after coal seam extraction and debris accumulation; bed separated fissures produced during the uncoordinated movement of each rock stratum due to different mechanical properties; broken fissures formed by the same rock stratum due to sinking and stretching; surface fissures formed by the development of rock stratum fissures to the surface.

The goaf of seams and overlying strata voids are channels for air leakage and oxygen supply, flue gas and heat dissipation for spontaneous combustion of coal seams, which determine the distribution of seepage field and gas concentration field in the coal fire zone, so that the mined-out area presents the uneven distribution pattern of gas concentration and airflow velocity. Zhuo et al. (2019) established a discrete fracture-pore model and multiphysics governing equations for the mined-out area, and used the FLUENT software to calculate the concentration distribution of O_2, CO and the distribution pattern of airflow velocity with fracture and pores, and the accuracy of the simulation results was confirmed by the oxygen concentration measured in the field. The study assumed that the physical and mechanical properties of the coal and rock mass in the mined-out area do not vary with time and temperature. However, in practice, the physical properties of

Fig. 6 Formation and development process of mining-induced underground coal fires



the coal and rock mass in the mined-out area usually vary with temperature. Xia considered this influence factor in his research and constructed a model for the evolution of permeability of underground coal seams (Xia et al. 2014). Lu and Qin (2015) considered the actual porosity distribution and obtained the airflow distribution and oxygen consumption data in the mined-out area by simulation with FLUENT software, and determined the hazardous area of coal spontaneous combustion with the oxygen concentration. The above study showed that generally, places with more fracture development have greater permeability and less resistance to gas flow and sufficient oxygen supply. In addition to gas concentration, gas flow rate is also a factor affecting spontaneous combustion of coal seams. Related studies showed that there exists a critical velocity of air flow in the mined-out area, and a velocity greater than the critical value will increase the heat exchange rate between air and solid material, increasing heat dissipation and inhibiting coal seam spontaneous combustion (Lu et al. 2022). Furthermore, it has also been shown that the advancing speed of the coal seam working face and the layout of the ventilation tunnel also have an impact on the airflow distribution. Liu (2014) explored the effects of factors such as propulsion speed and ventilation volume of different working faces on the oxygen concentration field and temperature field through simulation. Brodny and Tutak (2018) considered the effect of working face ventilation on the gas flow in the mined-out area and found that the further away from the longwall working face, the smaller the airflow velocity in the mined-out area through numerical simulation.

Under the condition of continuous ventilation and oxygen supply, coal interacts with oxygen to release heat. When the heat generated by combustion is greater than the heat dissipated from the coal seam to the outside, the ambient temperature increases. The ways of heat transfer in the mined-out area mainly include heat conduction from the coal body and overburden strata and heat convection caused by gas flow. Heat radiation is more noticeable only under high temperature and high vacuum conditions, so the effect of heat radiation is usually ignored in the study of heat mass transfer law of underground coal fires (Lu et al. 2022). Through heat transfer, the temperature distribution within the mined-out area shows dynamic changes and can affect the distribution of other physical fields. On the one hand, the high temperature formed by underground coal fires can induce thermal deformation of coal rocks and form a mining and combustion coupling mined-out area, which causes new fractures or collapse of overlying strata. It forms a complex network of fissures linking above and below ground, which facilitates a continuous supply of oxygen. On the other hand, once the coal fire is formed, the temperature keeps increasing and the temperature difference exists between the subsurface high temperature reaction environment and the surface. Under the action of gas concentration gradient and temperature gradient, buoyant natural convection will be formed, and driven by it, fire heating air pressure will be formed, which becomes the driving force for continuous oxygen delivery to the underground fire zone and promotes the continuous expansion of the fire zone (Lu et al. 2022). Xia et al. (2014) constructed a model of coal seam permeability evolution

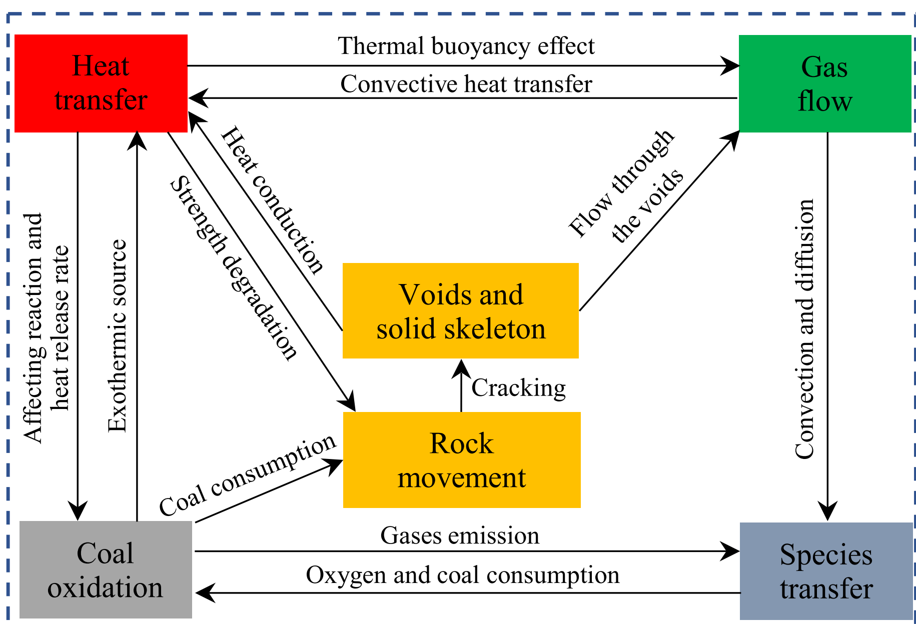


Fig. 7 Multiphysics coupling process of underground coal fires (Wang et al. 2016)

and analyzed the flow state of gas by considering that the temperature change during the coal oxidation reaction causes gas expansion and the subsequent gas pressure gradient affects the solid stress state. Song et al. (Song et al. 2019) considered the coupling effect of temperature gradient and concentration gradient on buoyancy, and established a buoyancy-driven natural ventilation platform to study the permeability change of rock strata in underground coal fire zones. Multiple fields interact with each other during the development of underground coal fires to form a cyclic thermodynamic process, which makes the underground coal fire spread in all directions continuously.

4.2 Multiphysics coupling models

As shown in Fig. 7, the development of underground coal fires is jointly affected by the chemical reaction field, gas seepage field, stress–strain field and temperature field, and the above fields also interact with each other. Many scholars have conducted quantitative studies on their interaction laws, forming a complete theoretical system of multiphysics coupled model for underground coal fires.

(1) Governing equation of seepage field

The gas flow in the underground coal fire zone is in accordance with the law of mass conservation and the theory of filtration in porous media. Within the control body, the rate of change of gas is equal to the sum of the net gas flux and the amount of gas consumed or produced. Its mass conservation equation is as follows:

$$\frac{\partial \varepsilon \rho_{\mathrm{g}}}{\partial t} + \nabla\left(\rho_{\mathrm{g}} v_t\right) = \emptyset \tag{1}$$

where, ε is the coal rock porosity; ρ_{g} is the gas density, kg/m^3; and v_t is the gas flow rate, m/s; Ø is the gas adsorption or resolved source term, kg/m^3 s.

When underground coal fires occur, the gas is often in a high-temperature, low-pressure environment where the intermolecular forces of the gas can be neglected. It can be considered to be consistent with the ideal gas equation of state:

$$\rho_{\mathrm{g}} = \frac{M_{\mathrm{g}} p}{RT} \tag{2}$$

where, M_{g} denotes the molar mass of the gas, in g/mol; p denotes the pressure, Pa; R denotes the gas constant, J/mol K; T denotes the temperature, K.

In the area of underground coal fires, the gas flow is usually non-Darcy flow, and its inertial forces cannot be neglected, in accordance with the Forchheimer equation (Whitaker 1996; Wang et al. 2012).

$$-\nabla p = \frac{\mu}{k}\boldsymbol{v}_t + \rho_{\mathrm{g}}\beta_{\mathrm{F}}\boldsymbol{v}_t\left|\boldsymbol{v}_t\right| \tag{3}$$

where, μ is the dynamic viscosity of the gas, m^2/ s; k is the coal rock permeability, m^2; and β_{F} is the Forchheimer coefficient, which is related to the value of the permeability k.

Bringing Eqs. (2) and (3) into Eq. (1), we can get the governing equation of the seepage field of underground coal fires, which takes into account the effect of temperature change and coal rock porosity change on gas flow rate.

The gas flow in the underground coal fire zone conforms to the conservation of momentum equation, which is given by the Navier–Stokes equation for viscous incompressible fluids as follows:

$$\frac{\rho_{\mathrm{g}}}{\varepsilon}\cdot\frac{\partial v_t}{\partial t} + \frac{\rho_{\mathrm{g}}}{\varepsilon}\left(v_t\cdot\nabla\right)v_t = -\nabla p + \nabla\left\{\frac{\mu}{\varepsilon}\left[\left(v_t\right) + \left(v_t\right)^T\right]\right\} - \left(\mu k^{-1} + \beta_{\mathrm{F}}\rho_{\mathrm{g}}\left|v_t\right|\right)v_t + \mathrm{F} \tag{4}$$

The left side of the equation indicates the inertial force term, the first term on the right side indicates the pressure, the second term is the viscous force term, and the third term is the external force acting on the fluid within the control body. The mass conservation equation and the momentum conservation equation of the gas flow are solved simultaneously to obtain the distribution of the gas seepage field.

(2) Governing equation of temperature field

There is two-phase heat conduction and heat convection between the coal and rock mass and the gas within the control body, whose heat conduction obeys Fourier's law, and the energy conservation equation is established for the coal rock body and the gas, respectively, as shown in Eqs. (5) and (6) (Tong et al. 2010):

$$(1-\varepsilon)\rho_{\mathrm{s}}c_{\mathrm{s}}\frac{\partial T_{\mathrm{s}}}{\partial t} + (1-\varepsilon)\nabla\left(\lambda_{\mathrm{s}}\nabla T_{\mathrm{s}}\right) = hA\left(T_{\mathrm{g}} - T_{\mathrm{s}}\right) + Q_{\mathrm{s}} \tag{5}$$

$$\varepsilon\rho_{\mathrm{g}}c_{\mathrm{g}}\frac{\partial T_{\mathrm{g}}}{\partial t} + (1-\varepsilon)\nabla\left(\rho_{\mathrm{g}}c_{\mathrm{g}}\right)v_t T_{\mathrm{s}} - \varepsilon\nabla\left(\lambda_{\mathrm{g}}\nabla T_{\mathrm{g}}\right) = -hA\left(T_{\mathrm{g}} - T_{\mathrm{s}}\right) + Q_{\mathrm{g}} \tag{6}$$

here, ρ_{s} is the density of the solid, kg/m^3; c_{s} is the specific heat capacity of the solid, J/kg K; λ_{s} is the thermal conductivity of the solid, W/m K; h is the convective heat transfer coefficient, W/m^2 K; A is the internal surface area density, 1/m; and Q_{s} is the solid heat source, W/m^3. The first term on the left of Eq. (5) indicates the internal energy change of the coal and rock mass, the second term is the conduction heat exchange, the first term on the right is the gas–solid convective heat exchange, and the second term is the heat source of the oxidation reaction of the coal rock body. The first term on the left of Eq. (6) indicates the gas internal energy change, the second term is the heat difference between the gas flowing into and out of the control body, the third term is conduction heat exchange, the first term on the right is gas–solid convection heat exchange, and the second term is the heat source of gas oxidation reaction.

(3) Governing equation of gas concentration field

The gas components in the control body satisfy the law of mass conservation, and their diffusion process is in accordance with Fick's law. The mass conservation equation of gas components i is given in Eq. (7).

$$\frac{\partial\left(\varepsilon\rho_g m_i\right)}{\partial t} + \nabla\left(\rho_g v_t m_i\right) = \nabla\left[D_i \nabla\left(\rho_g m_i\right)\right] + \varnothing_i \tag{7}$$

where, m_i is the percentage content of gas component i; D_i is the diffusion coefficient, m^2/ s. The first term on the left of the equation denotes the mass change within the control body, the second term denotes the mass difference between the flow of gas component i into and out of the control body, the first term on the right denotes the mass difference due to gas diffusion, and $\varnothing_i$ denotes the mass of gas produced or consumed by the reaction where, according to the Arrhenius equation, the chemical reaction rate is (Lichtner 1996):

$$r_i = -nc_s c_i A e^{-\frac{E}{RT}} \tag{8}$$

where, n is the correction factor; A is the pre-exponential factor, 1/s; E is the reaction activation energy, kg/mol.

The concentration distribution of each gas component can be obtained by bringing the following Eqs. (9) and (10) into Eq. (7).

$$\varnothing_i = M_i \cdot r_i \tag{9}$$

$$c_i = \frac{\rho_i m_i}{M_i} \tag{10}$$

where, M_i is the molar mass of gas component i, g/mol; r_i is the rate of production or consumption of gas component i; c_i is the concentration of gas component i; ρ_i is the density of gas component i, kg/m^3.

(4) Governing equation of coal and rock deformation

The coal and rock deformation in the underground coal fire zone is consistent with the linear elastic theory, and its total strain is equal to the sum of the strain caused by stress, pore pressure and thermal expansion. The stress–strain principal equation is as follows (Zhu et al. 2011):

$$\sigma_{ij} = 2G\varepsilon_{ij} + \left(K - \frac{2}{3}G\right)\varepsilon_{kk}\delta_{ij} - 3K\beta\frac{\partial T}{\partial t}\delta_{ij} + \alpha p\delta_{ij} \tag{11}$$

where, σ_{ij} is the stress tensor, Pa; ε_{ij} is the strain tensor; $G = \frac{E}{2(1+\upsilon)}$ is the shear modulus, Pa; $K = \frac{E}{3(1-2\upsilon)}$ is the bulk modulus, Pa; E is the Young's modulus, Pa; υ is the Poisson's ratio; β is the coefficient of thermal expansion of the solid, 1/K; α is the Biot number; δ_{ij} is the Kronecker symbol.

Stress balance equation for porous media:

$$\sigma_{ij,j} + f_i = 0 \tag{12}$$

where $f_i(i = x, y, z)$ is the component of net volumetric force in the direction i.

The relationship between displacement and strain is shown below:

$$\varepsilon_{ij} = \frac{1}{2}\left(u_{ij} + u_{ji}\right) \tag{13}$$

where u_{ij} is the displacement component, in m.

The above Eqs. (1), (4), (5), (6), (7) and (11) constitute the multiphysics coupled governing equations for underground coal fires. The parameters needed in the governing equation are obtained through coal oxidation experiments, and reasonable boundary conditions are determined, i.e., the distribution states of fire zone temperature, gas flow rate, and gas concentration can be obtained by numerical simulation. In addition, some scholars have expanded the theoretical content of the underground coal fire control model by considering more influencing factors in the multiphysics coupled model based on the actual situation. For example, Yang (2015) took into account the effect of buoyancy force caused by temperature increase on gas flow. Zheng et al. (2021) considered the change of porosity and permeability for coal and rock mass in the multiphysics coupled model and established a permeability evolution model. Song (2015) considered the gas flow under different pore states in the flow field governing equation in the fire zone, respectively, and concluded that the gas flow in the coal and rock matrix or fine-grained coal pile is consistent with Darcy's law and its inertial force can be neglected; the gas flow in the large-grained coal pile or coal gangue is faster, which conforms to Brinkman's law. In addition, he (Song 2022) proposed an oxygen-limited and self-sustained fire propagation model which considers the effect of thermal buoyancy on gas flow velocity and the effect of limited oxygen concentration on chemical reaction rate. This model was validated by lab experimental data.

4.3 Numerical simulations

The construction and application of the large-scale similarity test platform has effectively promoted the study of the multiphysics coupling law of underground coal fires, but also has limitations such as high cost and long test period. Consequently, many scholars also study the multiphysics coupling law of underground coal fires by numerical simulation method.

Earlier scholars considered the effects of only a few physical fields in numerical simulations to study underground coal fires. Wessling et al. (2007, 2008) focused on the calculation of oxygen consumption and supply rates during coal oxidation, and established a two-dimensional unsteady-state mathematic model considering the effects of temperature and seepage fields. Wessling et al. did not consider the coal and rock deformation during oxidation and combustion in the proposed model. In fact, the increase in temperature during coal seam combustion will cause changes in the stress state of its overlying rock strata, which may generate new fractures or even collapse, and has an important impact on the development pattern of coal fires. Zhai et al. (2011) established a steady-state seepage model for the coal seam mined-out area, and used the Fluent software to obtain the oxygen volume concentration and flow rate distribution at different locations to analyze the oxygen seepage rule. In this model, the researchers treated the coal spontaneous combustion process as a slowly changing steady-state process and considered only the effect of the seepage field, without considering the effect of temperature changes and the development of overlying strata fractures in the coal seam on the gas flow during the actual process.

With the continuous development and improvement of the numerical simulation technology and multiphysics coupling theory, the evolution mechanism of underground coal fires has been more fully studied. Zhang et al. (2006) used the finite element method for numerical solution to obtain the distribution of seepage velocity field, temperature field and oxygen concentration field in the top-coal caving region. On this basis, they divided the area most prone to spontaneous combustion and analyzed the mechanism of spontaneous combustion in the top-coal caving region. Zhai et al. (2010) established a thermal-fluid–solid coupling damage model for high-temperature rock masses based on the coupled model of temperature field, seepage field, and stress–strain field considering effects of damage and thermal convection. Xia et al. (2014) numerically simulated a thermal-fluid–solid coupling model of spontaneous combustion in an underground coal seam of a coal mine by COMSOL software to derive the temperature field, oxygen concentration field distribution, and airflow state of the porous coal medium at different periods, and verified the accuracy of the model in predicting the time and location of ignition by actual observation data. Song (2015) deduced the formula for calculating the oxidation and combustion rate of coal at high temperature stage, constructed a multiphysics coupled coal fire model by COMSOL software, and analyzed the effects of air leakage from the abandoned tunnel and atmospheric pressure cycle fluctuation on the flow field, temperature field and spreading of coal fires. The research of Song et al. improved the deficiencies of previous research on the diffusion mass transfer theory of coal oxygen reaction and perfected the multiphysics coupled model of underground coal fires. Wang et al. (2022) constructed a multiphysics coupled coal spontaneous combustion model by COMSOL software and analyzed the influence rule of the different oxygen concentration, ventilation and working face advancement speed on high temperature areas, and the simulation results were confirmed experimentally.

More and more scholars have started to focus on the research related to accidents such as gas explosion caused by coal seam combustion with the gradual improvement of the study of multiphysics coupled disaster-causing mechanism. Zhang (2011) established a multi-process coupled mathematical model of temperature field, gas pressure field and coal seam deformation field by considering the gas pressure and its desorption, and conducted numerical simulation. Han (2013) established a thermal-fluid–solid coupling model for desorption and adsorption of gas-bearing coal based on the basic theory of coal deformation and gas seepage by considering the effect of temperature effect on gas occurrence and coal body deformation. Li et al. investigated the dominance of gas flow in pore fissures of coal bodies under different temperature conditions, and established a numerical model of thermal-fluid–solid coupling of gas-bearing coal bodies by COMSOL finite element software, and simulated coal body fissures based on Monte-Carlo methods, and studied the flow characteristics of gas in fully connected fractures, partially connected fractures and pores under four test temperature conditions. Zheng et al. (2021) constructed a thermal-fluid–solid coupling model of coal fires in the mined-out area and simulated the distribution pattern of oxygen, gas concentration and temperature fields at different fire locations by COMSOL software. Duan et al. (2020) established a model of atmospheric pressure fluctuation and air leakage to analyze the effect of gas gushing amount within the confined fire zone on the oxygen concentration in the fire zone, and concluded that gas tends to accumulate within the confined fire zone and that there is a higher probability of gas explosion.

The above studies have demonstrated the law of heat and mass transfer and multi-physical field coupling process in the combustion affected area of coal seams, but it is still difficult to fully grasp the development pattern of underground coal fires under the joint action of multiple fields due to the cross-scale, non-homogeneity and anisotropy of the medium in the combustion affected area of coal seams. Hence, the evolution law of coal fires in the mining and combustion disturbed zone under multi-factor coupling conditions is still the focus and difficulty of underground coal fire research.

4.4 Laboratory experiments

Small-scale tests focus on exploring the intrinsic mechanism of the reaction between coal and oxygen, while the large-size test platform can simulate the real conditions of underground coal fires. In such case, the heat mass transfer law of coal spontaneous combustion is studied by monitoring the temperature change of coal samples in the experimental furnace and releasing gaseous products to reveal the non-uniform heat field, gas distribution, hot spot migration movement and other laws from a macroscopic perspective.

Research related to large-scale test platforms for underground coal fires already appeared in the 1980s, but early studies were less successful due to large radial heat losses from experimental furnaces and other reasons. The accuracy of the experiment was improved in subsequent studies by improving the experimental setup and controlling the temperature difference between the coal body and the fireplace to reduce the radial heat loss. Chen and Stott et al. (Chen and Stott 1997; Stott et al. 1987) built a coal self-heating furnace and arranged heaters and insulating foam on the furnace wall to reduce the radial heat loss, and analyzed the oxygen consumption rate of different coal samples to study the oxidation characteristics during coal self-ignition. This experiment is considered to be the first successful large-scale study of coal spontaneous combustion. Wen et al. (2017) investigated the whole process of the oxidation and spontaneous combustion of coal by the programmed heating method, and obtained the spontaneous combustion characteristics of experimental coal samples from room temperature to 450 °C at different oxygen concentrations. Deng et al. (2015, 2021) built an experimental platform that can be loaded with 15t of coal, and the temperature difference between the furnace wall and the coal sample was controlled by the water bath layer to make the reaction conditions closer to the actual situation of underground coal fires. In addition to the improvement in reducing unnecessary heat loss, many scholars have conducted similarity experimental studies between the mined-out area and coal seam to further investigate the development mechanism of underground coal fires by considering factors such as coal seam inclination, overlying stratum fissures and ventilation methods. Hao et al. (2019) simulated the structure of overlying strata in the mined-out area with lightweight porous foam materials, constructed a similarity experimental platform for fissures of overlying strata, and analyzed the oxygen concentration distribution in the mined-out area. Su et al. (2020) built a similar test platform for the sharply tilted longwall mined-out area, analyzed the effect of gas flow and ventilation on oxygen concentration in the mined-out area, and proposed a quantitative determination method for the spontaneous combustion risk zone in the steeply dipping longwall mined-out area based on the oxygen concentration gradient. Song et al. (Song et al. 2019, 2020a, b) proposed a model of thermal-solutal buoyancy driving air flow through coalbed, and developed a 1/20 scale hydraulic-thermo-chemical (HTC) coupled experimental research framework to analyze the relationship between the buoyancy driving model and the fire depth. In addition, they also used this experimental device to analyze the gas products of underground coal combustion, which is of great significance for the study of carbon emissions of underground coal spontaneous combustion. It is the first experimental work in the literature that has been demonstrated with capability to mimic HTC coupled process of underground coal fires. The above large-scale test platforms can simulate the actual physical conditions of coal spontaneous combustion to a certain extent, and reflect the dynamic evolution law of temperature field, gas flow field, chemical field, etc. However, during the high temperature combustion stage of coal seams, the fracture morphology of overlying strata changes significantly, and the permeability change affects the gas flow state. Therefore, there are still many challenges to be solved in the large-size experimental study of underground coal fires.

5 Prevention and extinguishing technology of underground coal fires

Underground coal fires are complex system engineering, with the characteristics of hidden fire source, oxygen-poor oxidation, complex causes, easy after-combustion, and difficult prevention and control (Deng et al. 2014). Therefore, fire preventing and extinguishing materials and technical equipment have been a hotspot of research and exploration, and various new materials and fire extinguishing technologies have realized the development of transformation from mechanism to practical application.

5.1 Key elements of fire extinguishing

Combustibles, oxygen and temperature are the "three elements" of combustion. For underground coal fires, the same three conditions must be met: the presence of combustibles, continuous oxygen supply conditions, and heat accumulation (Qi and Zhang 2010). Correspondingly, coal fires can be managed from the above three aspects, in order to destroy the three conditions to achieve the effect of fire extinguishing. The mechanism of action of various types of fire extinguishing materials and the importance of void distribution

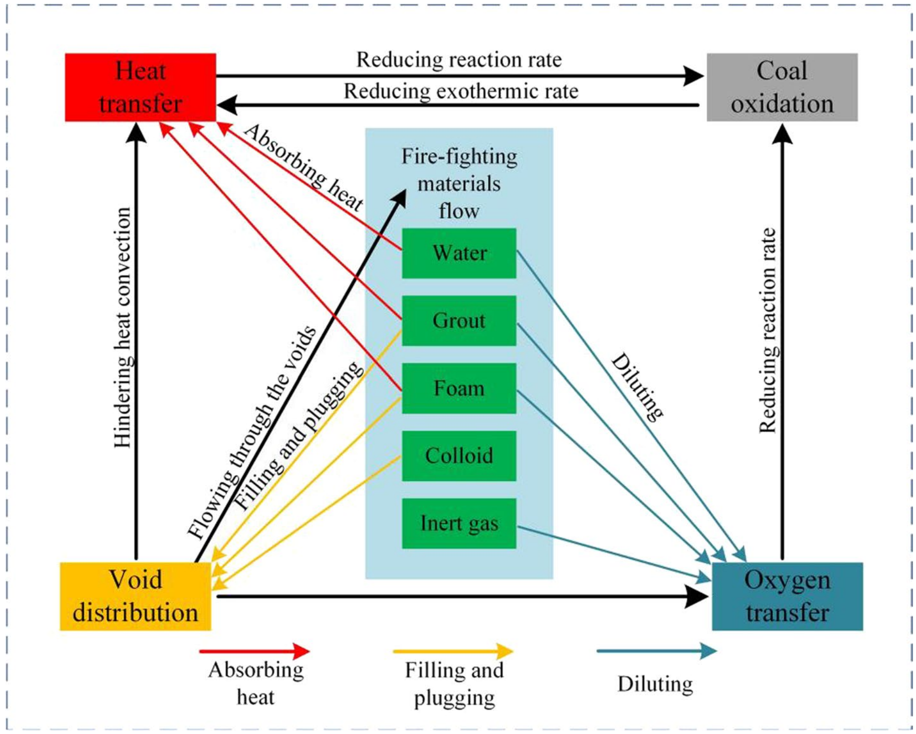


Fig. 8 Mechanism of action of fire extinguishing materials (Wang et al. 2016)

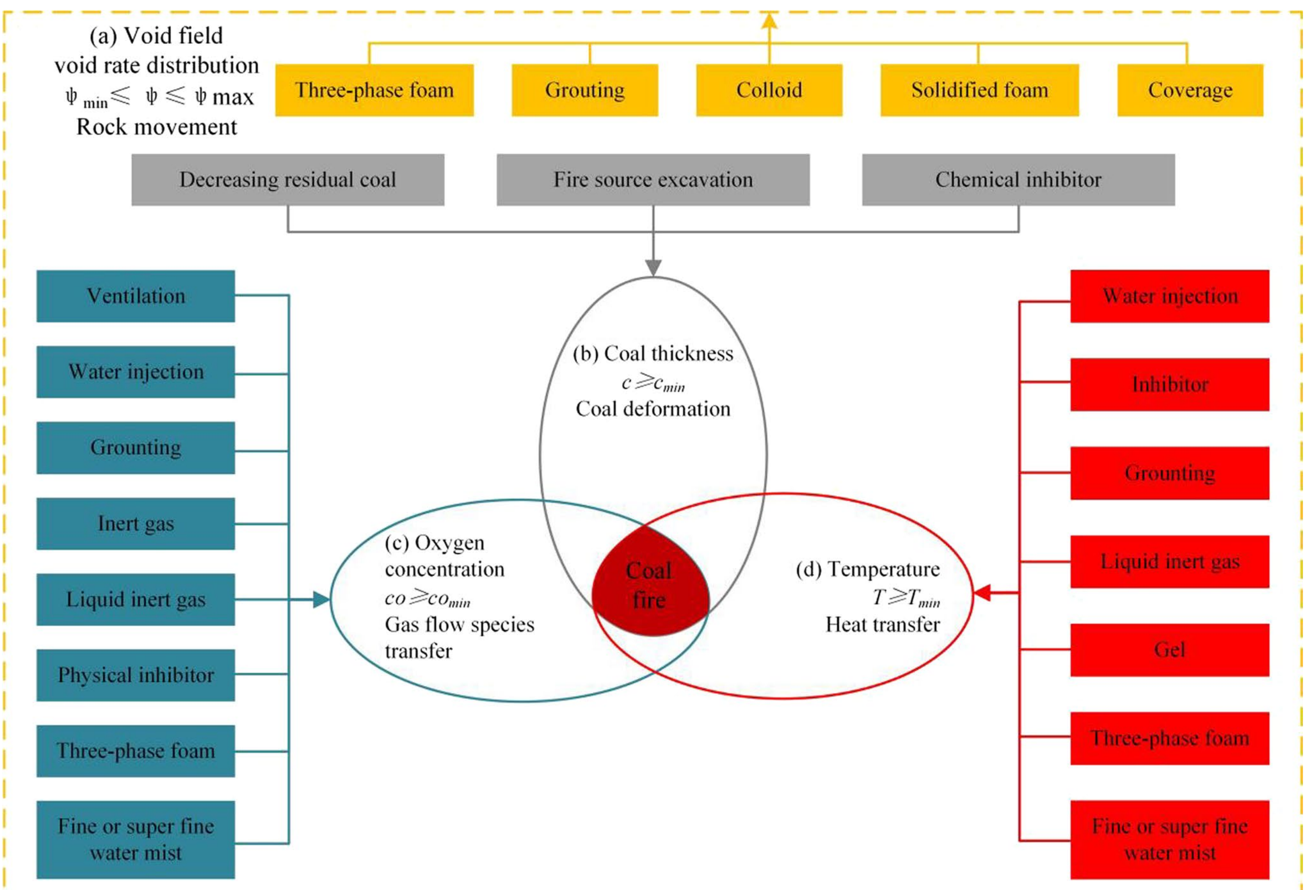


Fig. 9 Diagram of the multiphysics coupling mechanism and fire prevention mechanism of underground coal fires (Wang et al. 2016)

for the flow of fire extinguishing materials are illustrated in Fig. 8.

The distribution of voids determines the flow area of fire extinguishing materials, and the fire extinguishing materials in the area then control the coal fire through three processes: heat absorption, filling and blocking of voids, and dilution of inert gas. The effect of lowering the reaction rate and reducing the exothermic rate is achieved by lowering the temperature, reducing the oxygen supply channel, lowering the oxygen concentration and increasing the gas circulation resistance, respectively, so as to realize the management of coal fires.

5.2 Fire prevention and extinguishing technology

The void field and coal block distribution field induced by mining, the oxygen concentration field and temperature field in the underground space environment, together constitute the main environment of underground coal fires, as shown in Fig. 9.

The overall prevention and extinguishing of underground coal fires should comply with the principles of prevention-oriented works, early warning, local conditions, and comprehensive management, and control or eliminate one or more elements from coal, temperature, oxygen, and voids, as shown in Fig. 9. The technical means and materials used at home and abroad for fire prevention and extinguishing include excavation, water injection, slurry injection, colloid, curing foam, three-phase foam, high-density foam, liquid nitrogen, liquid inert gas, and water mist spray (Wang et al. 2014; Singh et al. 2004; Zhou et al. 2013; Wang et al. 2004; Zhou et al. 2006; Shao et al. 2015; Wang 2014b; Zhang et al. 2014). Based on the corresponding elements of control and the main functional roles, the fire prevention and extinguishing technologies for coal fires can be broadly classified into five major categories: direct stripping technology, air leakage control technology, endothermic cooling technology, inerting technology, and coal inhibition technology (Qi and Zhang 2010; Liang et al. 2016; Wang 2020).

5.2.1 Direct stripping technology

Direct stripping technology refers to the direct stripping of the fire source from the fire area. Usually, water is injected to cool down the shallow area first, and then the stripping process is completed by mechanical means or blasting, such as the separation of the coal from the fire source by excavation or directional blasting. Lv et al. (1996) earlier investigated the method of stripping the fire source by high-temperature blasting in the fire zone to solve the problem that the blast hole temperature is too high for normal blasting. Restricted by the strippable conditions of the fire zone, direct stripping technology is suitable for coalfield fire zones with small area, shallow burial and slow development. Stripping construction has such defects as complex process, large extinction cost and poor construction safety. Moreover, the stripping construction process brings the fire area in contact with oxygen over a large area, which may lead to the development and spread of the fire zone and cannot eradicate the threat of the fire zone.

5.2.2 Plugging fire prevention and extinguishing technology

Plugging fire prevention and extinguishing technology refers to the prevention or reduction of oxygen supply to the fire zone by filling and blocking the air leakage channels, which can be done by covering, sealing and equalizing pressure. Covering is a means to isolate the fire zone from oxygen with loess and other materials, which is technically easy, inexpensive and fast to construct (Deng et al. 2012). However, it is generally difficult to completely extinguish the fire zone, especially the heat storage fire zone. Covering is often used as an auxiliary measure in the comprehensive fire extinguishing process (Wang 2020). Sealing air leakage channels is also one of the means of fire extinguishing. Foam slurry was used earlier as a sealing material abroad and developed gradually (Colaizzi 2004), while traditional materials such as mud and clay minerals were developed to new materials in China, including three-phase foams (Wang 2004; Liang et al. 2006; Qin et al. 2014a, b), colloid (Deng et al. 2012; Wang 2014a), composite colloid (Liang 2010), inorganic curing foams (Lu 2015; Qin et al. 2014a, b; Xi et al. 2021), gel foams (Cao et al. 2012; Shen et al. 2017), and polymer blocking materials,, and they have been applied (Wen and Xu 2001; He et al. 2006; Peng et al. 2020). The polymer plugging material can expand dozens of times in volume during the process of action to achieve the effect of fully sealing cracks and channels. Traditional materials have limited material diffusion when sealing the air leakage channels, and cannot be applied to the management of large coalfield fire zones. New materials have good sealing effect but complicated construction and high cost. Pressure equalization technology is used to stop or inhibit the development of coalfield fires by reducing the pressure gradient and balancing the differential pressure of air leakage, which is often used as an auxiliary fire extinguishing method (Wang and Zhang 1994).

5.2.3 Endothermic cooling technology

Endothermic cooling technology refers to the technique of extinguishing the fire area by reducing the temperature. Heat absorption is generally achieved by filling the fire zone with materials that absorb heat quickly and have a high specific heat capacity. The common technical means include water injection, slurry injection, and foam injection. Water, slurry (Lu 2015), and foam materials (Dong et al. 2017) are all low-priced and easily available for the common situation of coalfield fire management. However, because of its large fluidity, the material always flows along the low terrain and cannot be accumulated at high places, so it is difficult to control the effective, uniform and full coverage of the fire zone. The emergence of two-phase foams has significantly improved the diffusion performance of water to make up for the limited efficiency of water fire extinguishing, but there is still the problem of easy rebound of fire zone management after the heat dissipation of foams. With the development of materials science, the three-phase foam fire prevention and extinguishing technology (Wang 2004), which integrates the performance of solid, liquid and gas materials, has shown advantages in wrapping, endothermic cooling, oxygen isolation and leak plugging. Water mist (Tang et al. 2019; Shao et al. 2015) cooling is developing as an effective measure for coal fire prevention and control. To improve the applicability of fine water mist technology, Si (2019) proposed a self-aspirating water mist generating device with the advantages of easy operation and high atomization.

5.2.4 Fire zone inerting technology

Fire zone inerting technology refers to the technology of injecting inert gas into the combustion fire zone, thereby reducing the oxygen concentration to asphyxiate the fire zone (Wang 2020). Injectable materials include nitrogen, carbon dioxide, inert foams, and inert three-phase foams. As required by fire fighting, technical devices for nitrogen preparation and injection have been continuously improved, which can better dilute and suppress explosions. However, fire fighting is not efficient enough and there are still difficulties in application. Liquid nitrogen and liquid carbon dioxide are widely used in coal fire prevention and control owing to their rapid heat absorption and cooling effects (Deng et al. 2012; Zhou 2019). The inert gas foam technology is used to extinguish fires by adding a surfactant to water and then interacting with an inert gas to produce foams (Qi and Zhang 2010). The inert gas three-phase foam, on the other hand, improves the water into slurry, which has the feature of long-lasting action time and better fire extinguishing effect compared with the inert gas foam. In general, inerting technology applies to the management of confined fire zones with a limited area, and it is not effective for the management of large coalfield fire zones with fissure development and multiple air leakage.

5.2.5 Coal inhibition technology

Inhibition technology is a technique to reduce the oxidation activity of coal by spraying and pressure injecting inhibition materials to the coal body, and the commonly used materials (Ma et al. 2015) are salts, atomized inhibitors, and polymer inhibitors. Calcium chloride and magnesium chloride have good water absorption but ordinary inhibition effect, while polymeric inhibitors have excellent blocking effect but expensive materials and limited blocking life.

Judging from the status quo of comprehensive treatment of underground coal fires, five types of technologies, namely direct stripping technology, air leakage control technology, endothermic cooling technology, inerting technology, and coal inhibition technology, have their own advantages and also have certain limitations. Therefore, it is difficult to use a single technology to meet the requirements of long-term plugging air to prevent spontaneous combustion of coal. Direct stripping can directly remove the source of the fire, but it is difficult to ensure the safety of the operation, and may also increase the fire. Water injection and grouting are low-cost and easy to operate, but have a limited diffusion range and are difficult to control consistently for construction. Gel and curing foams can fill the void better, but have a smaller diffusion range and limited fire extinguishing ability. The three-phase foam is easy to accumulate, but it is fragile and difficult to act permanently on the fire zone. Liquid nitrogen and liquid carbon dioxide can extinguish fires, but their storage and transportation processes are complex and costly. Water mist with low water consumption and low cost can cover and cool the fire zone. It demonstrates a good fire extinguishing effect, but has a poor migration ability, difficult to achieve large-area fire extinguishing. Consequently, continuous research on new fire preventing and extinguishing materials is a key means to drive the management of underground coal fires.

6 Beneficial utilization technology of underground coal fires

When stripping, plugging, cooling, inerting, inhibition and other means in underground coal fire prevention and extinguishing technology are used, the heat energy of coal fires is usually regarded as the source of disaster, and they are

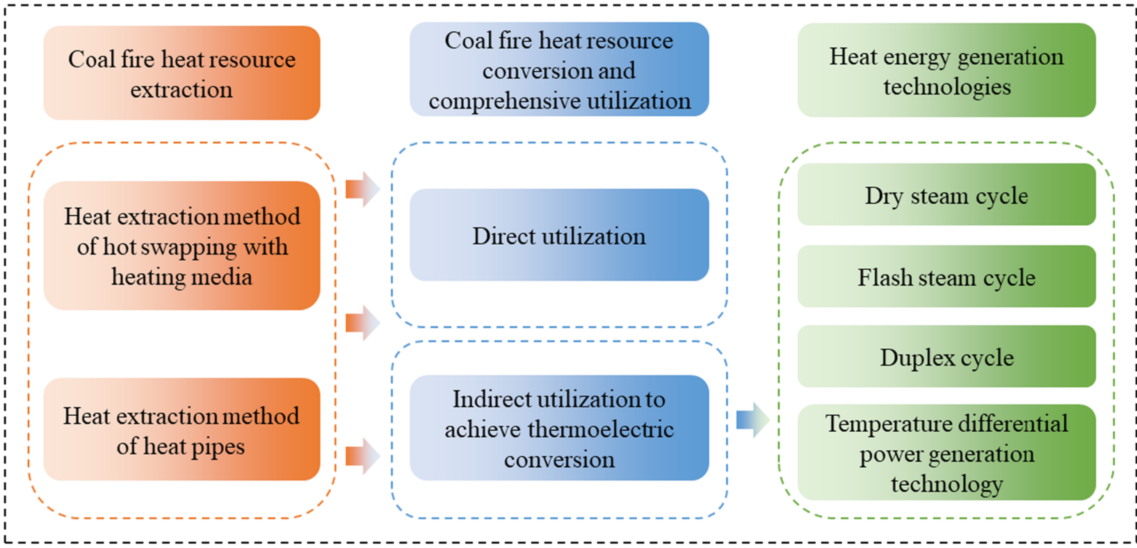


Fig.10 Beneficial utilization technology of underground coal fires

the means of directly abandoning coal mines without considering the extraction and utilization of its heat energy. In fact, the heat in the fire zone contains abundant waste heat resources, which can be used as low-moderate grade geothermal resources to some extent (Su, et al. 2020). Kurten et al. (2015) . demonstrated the feasibility of coal fire geothermal utilization by studying the geothermal extraction and utilization of abandoned mine piles in the western region of Germany. It is an important direction to solve the problem of underground coal fires by changing the idea of eliminating the "harm" of coal fires to "turning harm into benefit" of coal fires. According to statistics, the annual energy generated by underground coal fires worldwide exceeds the total energy produced by global hydroelectric power generation, which is almost 2.5 times the total capacity of 500 nuclear power plants worldwide (Shi et al. 2017). In view of the shortcomings of current coal fire management methods, we used the idea of "turning harm into benefit", i.e., changing "managing disaster sources" to "using heat energy in coalfield fire zones as a clean energy source", explored the development of waste heat resources in harmful underground coal fires, and carried out favorable research and engineering application of heat energy recovery. It is of great significance to accelerate coal fire management, energy conservation and emission reduction (Zhou et al. 2021). The beneficial utilization technology of underground coal fires is summarized in Fig. 10.

6.1 Coal fire heat resource extraction

Currently, the research on heat energy extraction from coalfield fire zones is still in the exploration stage. In order to successfully obtain underground heat energy and convert it into a usable form of energy, a series of heat extraction technologies and systems have been proposed at home and abroad, such as the heat pipe technology, heat pump technology, Organic Rankine Cycle (ORC) system, enhanced geothermal system, and heat pipe heat transfer system. (Chaudhry et al. 2012; Srimuang and Amatachaya 2012; Jouhara et al. 2017). For the unique geological conditions and heat storage in coalfield fire zones, heat pipe technology and hot swapping with heating media are the two main heat extraction methods today (Zhou et al. 2021).

6.1.1 Heat extraction method of hot swapping with heating media

Hot swapping with heat media is to use heat extraction media, i.e., heating media, to replace and extract heat energy from the fire zone and then convert it into electrical energy, and achieve fire area management by extracting and utilizing heat from the fire zone. Chiasson et al. (2007) analyzed data from actual cases, proposed the concept of extracting heat energy from underground coal fires and waste coal piles, simulated the heat exchange process of heating medium exchangers in vertical borehole casing, and established a temperature response factor model for vertical heat energy extraction boreholes to evaluate the economics and feasibility of power generation from underground coal fires and waste piles. Zhong et al. (2016a, b) compared the heat extraction effects of solid, liquid and gaseous heating media, analyzed the advantages and disadvantages of two heat extraction methods, buried pipe heat extraction and direct pressure injection heat extraction, and proposed a fire zone heat extraction and conversion method using gaseous heating media as the carrier heat extraction and multi-hole press-in guided heat extraction with the ORC system for power generation. However, the overall heat exchange and thermoelectric conversion are less efficient due to the complex conditions such as uneven rock density and uneven temperature distribution in the coalfield fire zone, and technical problems such as efficient graded conversion of heat energy need to be studied in more depth.

6.1.2 Heat extraction method of heat pipes

Heat pipes are a kind of heat transfer elements with excellent heat transfer performance and isothermal performance, with excellent one-way thermal superconductivity, and can be flexibly applied to a variety of environments. Gravity heat pipes are a kind of heat pipes, and its working principle is that the medium relies on gravity to realize the circulation. It consists of three parts, one section is the evaporation section to absorb heat and make the fluid evaporate, the middle is the adiabatic section to complete the circulation, and the other end is the condensation section to condense steam and disperse heat, which can effectively transfer a large amount of heat without additional power input. Compared with ordinary heat pipes, gravity heat pipes have the advantages of simple structure, convenient manufacturing, lower cost, reliable operation, flexible and variable structural form and type size (Chaudhry et al. 2012; Jouhara et al. 2017).

In a patented technology, the Ohio General Engine Company has proposed a "heat transfer element". In the 1960s, Grover et al. formally introduced the name "heat pipe" in their patent and published the experimental research results. Theoretical research on heat pipes began to develop, and heat pipes were also widely applied due to their high thermal conductivity for heat transfer and energy recovery (Qu 2014). In the 1980s, the heat pipe technology in China was rapidly developed and popularized, which brought significant energy-saving benefits, and the research on gravity heat pipes by researchers and technicians was mainly focused on the basic theory and engineering applications. Guo et al. (Guo and Liu 2007; Peng et al. 2004) added nanoparticles to the working medium to improve the heat transfer performance of gravity heat pipes. Sarmasti (2008), Jouhara and Robinson (2010) and others conducted experimental studies on gravity heat pipes to reveal the effects of factors such as aspect ratio, liquid filling rate, inclination angle, and working media on the heat transfer performance of gravity heat pipes. Qu (2014) observed the spontaneous combustion phenomenon caused by heat storage and warming of coal during transportation and stacking, and proposed the application of gravity heat pipes to extract and transfer the heat generated by burning coal piles to stop the heat accumulation inside coal rocks, and proved through a series of studies that gravity heat pipes can be used for heat extraction in the fire zone, thus providing an idea for heat extraction in the fire zone (Zhang et al. 2017). The excellent heat transfer performance and economy of gravity heat pipes solve problems of geological environment and heat transfer efficiency in the process of deep geothermal development of coal fires, and lay the technical foundation for the efficient recovery of low-grade geothermal energy in coal fires at the present stage (Zhou et al. 2021).

The research and application of heat pipe heat transfer technology has received widespread attention in the context of the current sustainable development and carbon peaking and carbon neutrality goals, and has been highly emphasized in industries and fields such as waste heat recovery, automotive engines, geothermal energy, and solar energy (Zhuang and Zhang 2000); moreover. scientific research on heat pipes has been carried out from theoretical analysis, experimental studies, and numerical simulations (Qu 2014). How to improve the heat transfer efficiency, improve the economy, enhance the adaptability to complex engineering conditions and strengthen the R&D application of small heat pipe technology are important scientific problems in the development of heat pipe heat transfer technology.

6.2 Coal fire heat resource conversion and comprehensive utilization

The utilization of geothermal energy can be divided into two main categories: direct utilization, such as space heating, pipeline heating, industrial and agricultural heat, and domestic heat, and indirect utilization to achieve thermoelectric conversion (Lund et al. 2011). Since underground coal fires usually occur in remote or uninhabitable areas, there is less need for direct use of heat energy. Hence, conversion of heat energy to electrical energy is the most feasible technical route at present. The current mainstream heat energy generation technologies are dry steam cycle, flash steam cycle and duplex cycle (Dippippo 2015). In the field of underground coal fire heat energy utilization, the main power generation technologies are organic Rankine cycle power generation and temperature difference power generation in the duplex power generation cycle (Ren et al. 2017).

To ensure high power generation efficiency, the ORC power generation technology requires a large heat source capacity, which fits with the characteristics of underground coal fires with large heat energy release, so it is appropriate to use underground coal fires as the heat source of ORC (Ren et al. 2017). Zhong et al. (2016a, b) proposed a method of heat energy extraction and conversion in coalfield fire zones: They use flame retardant filling materials to cover the surface fissures, collapse pits and other air inlet and outlet channels in the high temperature area, drill holes in the surface and press the gaseous heat medium into the high temperature area of the underground coal fire through the gas booster pump. The heat exchange is completed between the gaseous heat medium and the high temperature area, and then completed through the vacuum pump, filter and evaporator. The heat energy obtained from the exchange is generated by the ORC system, and the remaining thermal medium is then cooled and re-entered into the low temperature storage tank, which is repressurized into the borehole by the booster pump to complete the cycle until the end of the extraction and conversion process. This method makes up for the defect that the heat energy contained in the treatment process of existing coalfield fire zones cannot be extracted, and achieves the effect of "turning waste into treasure" and "turning harm into benefit", which has a large number of industrial application examples in Europe and America (Wang et al. 2015). At present, the ORC system still has problems such as the difficulty to guarantee the service life of the system in the fire zone and difficulty in handling the equipment. Research and experimental studies on ORC power generation technology, component optimization, and engineering applications of generator sets are yet to be tackled (Wang and Gu 2008; Wang et al. 2015).

Temperature differential power generation technology is based on the theory of Seebeck effect, i.e., first thermoelectric effect, and efficiently converts heat from low-level heat sources into clean electricity by means of thermoelectric sheet components. It boasts many advantages such as easy manufacturing, easy maintenance, long life, no noise, environmental friendliness, and strong adaptability (Kajikawa 2009), which is widely used in various fields of heat energy recovery. Since 2015, Zhou Fubao's team has been conducting a large number of large-scale engineering experiments on heat recovery and utilization in coalfield fire zones in Xinjiang, and has built a global engineering test base for coal fire prevention and utilization. In 2016, the distributed heat energy extraction and thermoelectric power generation device developed by Zhou Fubao's team (2016) was successful in generating electricity in the Daquan Lake fire zone in Xinjiang Province, marking the effective recycling of waste heat energy in the coalfield fire zone. Afterwards, Zhou Fubao's team continued to conduct thermoelectric power generation simulation experiments and made improvements for the heat generating device to greatly enhance the system power generation, forming a new heat energy extraction thermoelectric power generation system for underground coal fires (Su et al. 2017, 2018; Zhou et al. 2017b). They developed a gravity heat pipe heat energy extraction thermoelectric power generation system by taking advantage of gravity heat pipes (Zhou et al. 2017c). Facing the new requirements of coal fire ecological management and green and low-carbon development, Zhou Fubao et al. (Su et al. 2020; Shi et al. 2017; Zhong et al. 2016a, b; Ren et al. 2017; Deng et al. 2020) synergistically considered green prevention and control of coal fires with heat energy ecological utilization, and proposed a new idea of coal fire management of "using instead of treating, ecological fire extinguishing, and sustainable development", and established an integrated system of heat energy utilization in coalfield fire zones (Qi et al. 2019) and an integrated system of heat energy utilization and surface ecological restoration of underground coal fires (Zhou et al. 2017d). In 2019, Zhang designed and constructed a new embedded heat energy extraction device for shallow boreholes in coalfield fire zones based on thermoelectric power generation technology. The device can be put into the shallow borehole for direct thermoelectric conversion, avoiding significant heat loss during thermoelectric conversion, and the output power of the thermal energy extraction device was increased by 16% in the test, but it still has shortcomings in adapting to heat extraction utilization conditions of the field borehole and power generation efficiency.

Currently, thermoelectric power generation is recognized as the most innovative and promising technology for energy saving and environmental protection. With the breakthrough of electric heating material development and equipment upgrade and the fine control of underground coal combustion, the scientific and engineering problems of the thermoelectric conversion efficiency, semiconductor material cost, self-sustained smoldering combustion, and long period stabilization, which limit the development and promotion of thermoelectric power generation technology, will be solved in the future, and the advantages of thermoelectric power generation technology in waste heat recovery and green utilization will gradually appear.

The efficient extraction and conversion of heat energy has been a cutting-edge research and hot issue in the field of underground coal fires (coalfield fires). By transforming the innovative and optimized application of traditional geothermal utilization technology in coalfield fire zones, we explore a comprehensive and efficient way of heat energy utilization in coalfield fire zones and a new model of prevention and control-utilization synergistic governance (Su 2018), forming an overall layout of waste heat power generation, coal fire management, and environmental restoration covering the whole process, as shown in Fig. 11. It aims to guide coal fire management to an economic, harmonious, and green sustainable development path.

7 Prospects for development direction of the prevention and control of underground coal fire hazards

As shown in Fig. 12, the prevention and control of underground coal fires can make breakthroughs and innovations in four aspects: coal combustion mechanism, multiphysics coupling effect, fire prevention and extinguishing technology, and coal fire conversion and utilization.

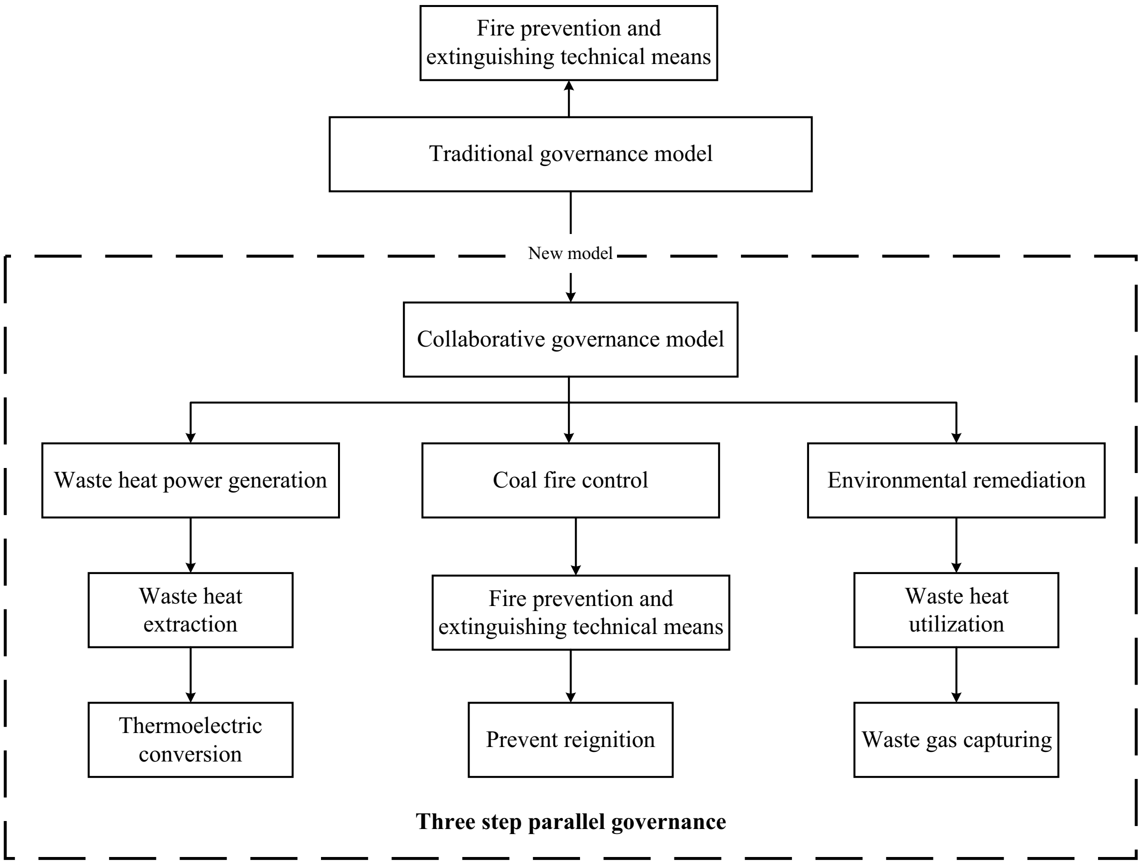


Fig. 11 New model of coal fire management

(1) Mechanism of coal spontaneous combustion. Basic properties such as coal seam composition and spontaneous combustion have significant effects on underground coal fires. Therefore, it is necessary to increase the research on the microscopic reaction mechanism of coal spontaneous combustion, especially the low-temperature oxidation reaction of coal, the study of the relationship between functional groups and temperature change, and the influence mechanism of inhibition substances on the process of coal spontaneous combustion to reveal its microscopic structural changes, so as to lay a solid foundation for the in-depth study of coal spontaneous combustion mechanism under complex environment. Meanwhile, comprehensive information records on combustion characteristics and characterization parameters of coal fire hazards in various regions are made to establish relevant databases, which will provide a reliable basis for scientific evaluation and prevention of coal fires.

(2) Multiphysics coupling effect. Under the dynamic action of thermal, fluid, solid and chemical fields, the factors affecting coal spontaneous combustion are complicated, and there is still a lack of research on the convection-driven mechanism caused by temperature gradient and gas component concentration gradient, etc. It is an important direction to explore the multi-factor coupling mechanism of coal spontaneous combustion to solve the scientific problem of coal fire prevention and control. It is an urgent need to solve key problems in underground coal fire research to grasp the macroscopic thermophysical field effect characteristics of coal spontaneous combustion at different stages under the coupling conditions of multiple factors, to establish the oxidation kinetic reaction model of spontaneous combustion process, and to reveal the reaction mechanism and change mechanism of coal spontaneous combustion under the coupling effect of multiple factors.

(3) Fire prevention and extinguishing technology. The long-term development of fire prevention and extinguishing technology requires the dual support of new materials and artificial intelligence. On the one hand, combined with the research on the key parameters of coal fire formation and evolution process and the development process of material science, we develop new

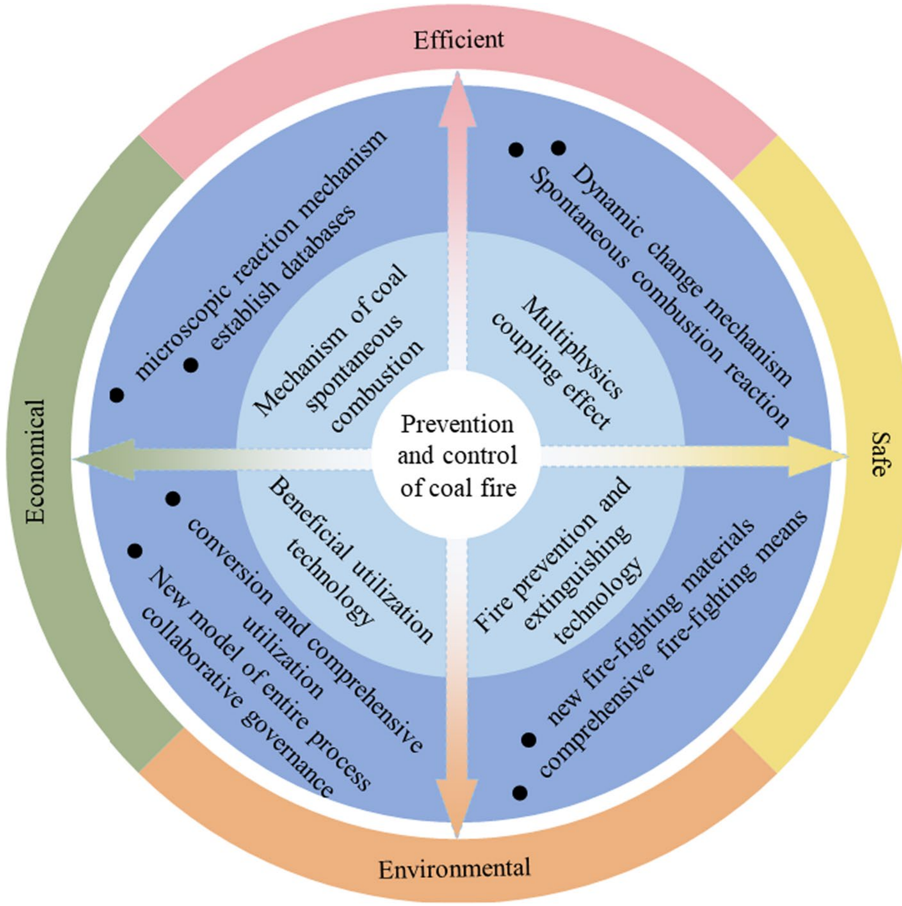


Fig. 12 Prospects for the prevention and control of coal fire hazards

fire prevention materials that are economical, efficient, green and safe, and accomplish the "basic reserve" of fire prevention and extinguishing. On the other hand, in the context of automation and intelligent development, we integrate the high precision technology scientifically, and choose the comprehensive fire prevention and extinguishing means with the combination of multiple fire prevention and extinguishing methods according to the coal seam conditions to achieve better suppression effect instead of single fire extinguishing technology, so as to innovate the mode of fire prevention and extinguishing.

(4) Beneficial utilization technology of coal fires. Underground coal fires are not only a geological disaster, but also contains a huge amount of heat energy for use. We change the management idea of "use before treatment" to the innovative idea of "turn harm into benefit", optimize the existing equipment and technology of heat energy extraction, improve the efficiency of heat energy conversion, and recycle the heat energy generated by coal fires in a safer, more efficient and green way, and finally realize the conversion and comprehensive utilization of coal fire. We will form a new model of the entire process of collaborative governance on prevention—utilization—restoration to make coal fire management more green and low-carbon and sustainable in development.

8 Conclusions

In this paper, we counted the relevant literature of underground coal fire research and summarized the hot issues of coal fire research in China. We sorted out the combustion mechanism, multiphysics coupling effect, and fire prevention technology of underground coal fires, and introduced the beneficial utilization technology of coal fires in detail. In addition, we elaborated the key research directions in the field of coal fire prevention and control from four directions, including the mechanism of coal spontaneous combustion, multiphysics coupling effect, fire prevention and extinguishing technology, and conversion and utilization of coal fires, expecting to provide reference for future research on prevention and control problems of coal fire hazards.

The mining-induced underground coal fire is a disaster problem generated along with coal resources mining, and its safe, efficient, economic, low-carbon, sustainable utilization and green control are important topics to be studied in the future. Traditional means of coal fire management are prone to ecological damage, and their limited management effect causes the fire area to be not easily extinguished completely. Therefore, prevention and control methods of underground coal fire hazards need to be further explored. The microscopic change law of coal spontaneous combustion, the reaction mechanism of coal spontaneous combustion under the action of multiphysics coupling effect and the mechanism of dynamic change all need to be explored in depth. It is also necessary to establish a database of basic coal seam parameters and develop new fire prevention and extinguishing materials to provide a basis for coal fire prevention and control. Based on equipment optimization and technology upgrade, we can improve the efficiency of fire extinguishing with comprehensive fire prevention and extinguishing instead of single fire extinguishing, and replace single process management with the entire process of collaborative governance, so as to fully realize the underground coal fire hazard of "turning harm into benefit".

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Declarations

Conflict of interest The authors declare no conflict of interest.

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