ACS OMEGA

http://pubs.acs.org/journal/acsodf

Review

Current Status of Research on the Coal and Gas Outburst Control Technology of Hydration and Anhydrous

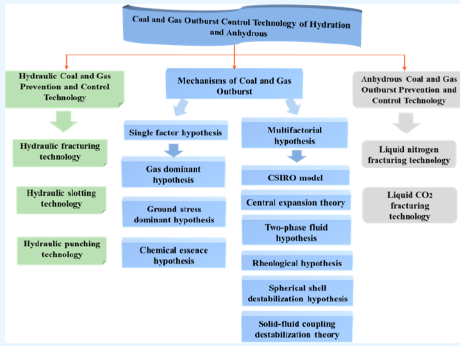
Jifen Zhang, Liguo Wang,* and Xiangjun Chen

Cite This: *ACS Omega* 2023, 8, 44472−44484

Read Online

ACCESS | Metrics & More | Article Recommendations

ABSTRACT: China is one of the countries with the most frequent coal and gas outburst accidents in the world. In the early years of the founding of New China, coal and gas outburst accidents occurred frequently, causing serious casualties, equipment damage, and economic losses. In recent years, some scholars have tried to simulate the coal and gas outburst phenomenon using physical models to study the mechanisms of its occurrence. However, due to the complexity and non-reproducibility of coal and gas outburst disasters, the study of coal and gas outburst mechanisms is still in the hypothesis stage. In order to effectively reduce the risk of coal and gas outburst accidents, coal and gas outburst prevention and control technology have emerged and achieved remarkable results, and the probability of coal and gas outburst accidents has been greatly reduced. Among coal and gas protrusion outburst and control technologies, hydraulic and anhydrous prevention and control technologies are widely used. The purpose of this paper is to briefly explain the mainstream hypothesis of coal and gas outburst, analyze the action principle of hydration and anhydrous control technologies, discuss the current status of research on hydration and anhydrous control technologies, and put forward the problems of current technologies and future development trends.



1. INTRODUCTION

According to the National Bureau of Statistics 2022 statistical bulletin on national economic and social development,[1] China's mining industry grew by 7.3%, with raw coal production at 4.55 billion tons, up 10.5% over the previous year, with coal production still accounting for more than 50% of total energy production. In recent years, new and renewable energy technologies have flourished, but for various reasons they cannot yet be applied on a large scale. Therefore, coal is still the pillar of China's economic development and stable energy supply and will continue to occupy an important position in the coming decades. Coal and gas outburst is a common accident disaster in the process of coal mining. Coal and gas outburst is a dynamic disaster without an obvious precursor. A large number of coal and gas mixtures are ejected instantaneously, causing casualties and economic losses. Coal and gas outburst accidents have occurred in mining areas in many countries. Among them, China is one of the countries with the most frequent coal and gas outburst accidents in the world.[2,3] With the continuous increase of coal production, the reserves of shallow coal continue to decrease, the depth of coal seam mining continues to deepen, the ground stress and gas content of coal seam gradually increase, and the permeability of coal seam gradually decreases.[4−6] This trend aggravates the intensity and frequency of coal and gas outburst disasters, which easily cause major accidents.

So far, it is known that there are many related factors leading to coal and gas outburst accidents and that the interaction among various factors is more complex. Therefore, a complete and unified theory of the coal and gas outburst has not yet been formed. In order to prevent the occurrence of coal and gas outburst accidents, corresponding prevention and control measures should be taken according to the actual mining situation. Among coal and gas outburst prevention and control technologies, hydration and anhydrous technologies are very effective means. Hydraulic coal and gas outburst prevention and control technology usually use high-pressure water as power, forcing the expansion and extension of primary fissures in coal reservoirs or artificially generating new holes and fissures, thereby promoting changes in gas and ground stress in coal and rock mass and avoiding coal and gas outburst accidents, mainly including the following: hydraulic fracturing, hydraulic slitting, and hydraulic perforation.[7−9] Nonhydrated coal and gas outburst prevention and control technology mainly use a nonaqueous material as the medium of coal seam fracturing and

Received: September 13, 2023
Revised: October 30, 2023
Accepted: October 31, 2023
Published: November 16, 2023

https://doi.org/10.1021/acsomega.3c07010
ACS Omega 2023, 8, 44472−44484

permeability enhancement, especially the cold impact of a low-temperature medium on a coal seam. Under multiple forces, the number of coal seam cracks gradually increases, the connectivity gradually increases, the permeability of the coal seam increases, and the probability of coal and gas outburst accidents is reduced. This technology mainly includes the following: liquid nitrogen fracturing, liquid CO_2 fracturing, and other technologies.[10,11] Aiming at the current trend of the coal mining industry and the requirements of coal mine safety production in the new era, this paper aims to briefly elaborate the mainstream hypothesis of coal and gas prominence, analyze the function principle of the role of hydraulic and anhydrous prevention and control technologies, study the current development status of hydraulic and anhydrous prevention and control technologies, explore the problems of existing technologies, and propose the trends of future development.

2. MECHANISMS OF COAL AND GAS OUTBURST

The process of coal and gas outburst includes four stages: preparation, excitation, development, and termination.[12] In the process of an outburst, ground stress and gas act together on the coal seam, making the coal, rock fragmentation, and gas to be suddenly thrown out from the coal seam to the mining space, accompanied by a strong sound and powerful impact power phenomenon; the whole process is extremely complex.[13] The mechanism of coal and gas outburst is the premise guiding the formulation of outburst prevention technology. Due to the complexity and nonreproducibility of coal and gas outburst hazards, most researchers can only base their research results on theoretical analysis, experimental simulation, and statistical data but not on direct observation of the process of an outburst. Therefore, only certain phenomena in the process of coal and gas outbursts can be explained at present, and the mechanisms of coal and gas outburst still remain at the stage of hypothesis, which has not yet formed a complete theoretical system widely recognized by academia.

2.1. Foreign Representative Coal and Gas Outburst Hypothesis. The hypothesis of coal and gas outburst mechanisms proposed by foreign scholars can be broadly divided into four popular hypotheses according to the different forces at the time of outburst: gas dominant hypothesis, ground stress dominant hypothesis, chemical essence hypothesis, and comprehensive action hypothesis. Among them, the gas dominance hypothesis, the ground stress leading hypothesis, and the chemical nature hypothesis are all single-factor hypotheses.[14] The amount of gas in a coal seam is an important influence on whether a coal and gas outburst occurs or not, and many researchers and scholars have studied the close connection between gas outflow and outburst and put forward the gas dominant hypothesis,[15] which suggests that high-pressure gas plays a dominant role in the outburst process, mainly including the following: cavity theory, gas pocket, body force theory, coal void structure inhomogeneity theory, gas expansion theory, gas desorption theory, etc., among which the "gas pack theory" is dominant.[16−18] The ground stress dominance hypothesis considers high ground stress as the main factor leading to the occurrence of an outburst, including aspects of self-weight stress, tectonic stress, and stress concentration in front of the working surface. This hypothesis also has several derivative hypotheses, such as rock deformation potential theory, stress concentration theory, tensile stress wave theory, Singh's mechanism,[19] and so on. The chemical nature hypothesis believes that some kind of chemical reaction occurs in the coal body, leading to the emergence of phenomena such as high-pressure gas and strong thermal effects, which further develop into a coal and gas outburst accident, and its main components include gas hydride theory, geochemical theory, nitro compound theory, etc.

In addition to the single-factor hypothesis, there is also the integrated action hypothesis. In the mid-1950s, the Soviet scholar Nekrasovski put forward the integrated action hypothesis of coal and gas outburst, which opened the stage of analyzing the mechanisms of coal and gas outburst from the perspective of integrated action.[20] The integrated action hypothesis believes that acoal and gas outburst is the result of the combined action of ground stress, gas inside the coal body, and the structural properties of coal. Since the combined action hypothesis has comprehensively considered all factors of the occurrence of coal and gas outburst, it has been widely recognized by scholars at home and abroad.[21] Based on the integrated action hypothesis, several hypotheses have been developed, such as vibration theory, stratification separation theory, destruction zone theory, free gas pressure theory, ground stress inhomogeneity hypothesis, and energy hypothesis. One of the more representative hypotheses is the "energy hypothesis" of coal and gas outburst proposed by Hodot, a former Soviet scholar[22] and the CSIRO salience model proposed by Wold, Choi, et al. of the Commonwealth Scientific and Industrial Organization (CSIRO) of Australia.[23] The "energy hypothesis" states that prominence is due to a combination of the deformation potential of the coal and the internal energy of the gas, and many of its ideas still have much to offer today. The CSIRO coal and gas outburst model generalizes the interaction among gas, stress, and coal body strength (as shown in Figure 1)

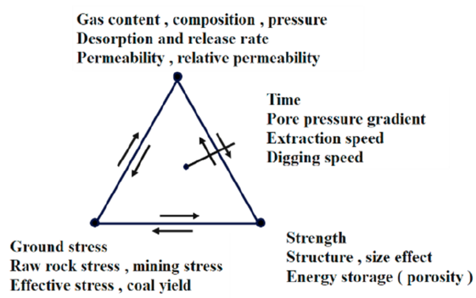


Figure 1. Relationship of coal and gas outburst influence factors in the CSIRO model. Reprinted from ref 23. Copyright 2015, with permission from the Journal of Rock Mechanics and Engineering.[23]

and considers the effect of gas ejected during coal and gas outburst with the gas−solid two-phase flow of crushed coal dust. Meanwhile, Chinese scholars are also studying the stress state of the protruding coal seam, the gas endowment state, and the physical and mechanical properties of coal and exploring the mechanisms of coal and gas outburst in depth through field data and experimental studies.

2.2. Domestic Representatives Highlighting the Hypothesis. Since the 1960s, Chinese scholars began to research the mechanisms of coal and gas outburst, put forward their own views based on the existing research results, and continuously improved and perfected the theoretical system of coal and gas outburst mechanisms. Representative hypotheses include central expansion theory, two-phase fluid hypothesis, rheological hypothesis, spherical shell destabilization hypothesis, solid−fluid coupling destabilization theory, etc.

https://doi.org/10.1021/acsomega.3c07010
ACS Omega 2023, 8, 44472−44484

Yu proposed the central expansion theory using geological mechanics, fracture mechanics, and excellent domestic practices. This theory suggests that the coal and gas outburst originates from the launch center at a certain distance from the working face and then spreads around. The coal−rock−gas system around the launching center provides coal and gas outburst energy and participates in the coal and gas outburst process. Because the coal and gas outburst process starts from a center and spreads around, the center of the coal and gas outburst is at the stress concentration point, and the point develops unevenly in all directions.[24,25]

Li analyzed the characteristics and phenomena of coal and gas outburst, introduced the concept of a two-phase fluid, and put forward the hypothesis of a two-phase fluid by studying the formation process of a two-phase fluid in the coal and gas outburst center. The hypothesis holds that the essence of a coal and gas outburst is to form a two-phase fluid of coal particles and gas in the center of the coal and gas outburst. The fluid is subjected to the action of deposited energy and released energy and breaks through the obstruction to cause a coal and gas outburst. At the same time, the hypothesis points out that the main driving force of the coal and gas outburst is not from the elastic energy and gas expansion energy of coal and rock but from the expansion energy of a two-phase fluid.[26]

Zhou and He proposed the rheological hypothesis by studying the rheological properties of gas-bearing coal samples under three-dimensional stress conditions (Figure 2). This hypothesis believes that a coal and gas outburst is essentially a rheological behavior of gas-bearing coal bodies, emphasizing that the manifestation, intensity, and scale of coal and gas outburst are controlled by a variety of factors, including ground stress, gas pressure, coal quality distribution, top and bottom slab lithology, and mining methods, as well as time and space conditions. Experimental results indicate that the coal and gas outburst process usually consists of three stages: the first two stages are the preparation stage of a coal and gas outburst, and the third stage is the development stage of a coal and gas outburst.[27]

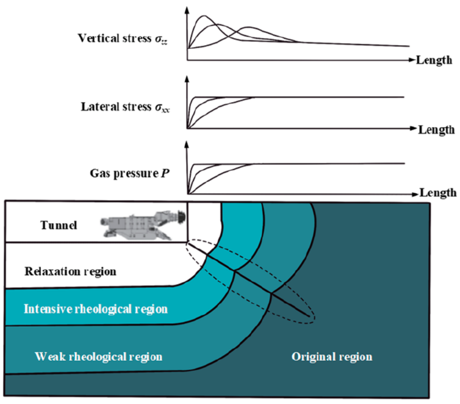


Figure 2. Rheological hypothesis of the coal and gas outburst mechanism. Reprinted from ref 4. Copyright 2023, with permission from Coal Geology & Exploration.

Based on the theoretical analysis of the coal and gas outburst process, Jiang and Yu put forward the spherical shell instability hypothesis and confirmed the two inferences of the spherical shell instability hypothesis through a large number of laboratory studies (as shown in Figure 3). The hypothesis is that in the coal body passing through the coal and gas outburst front, each coal body point experiences the original stress stage, the concentrated stress stage, the ground stress failure stage, the coal body gas tearing stage, the coal shell instability throwing stage, and the handling and static desorption stage. The essence of the process of coal and gas outburst is that ground stress destroys the coal body, the coal body releases gas, the gas expands the coal body crack and causes the coal shell to destabilize and destroy, and this throws out the surface damage coal body that originally has a supporting effect to the roadway, forcing the stress peak to move to the inside of the coal body and continue to destroy the subsequent coal body. The main driving force for the sustainable development stage of coal and gas outburst occurrence and development is the initial gas expansion energy released by coal body destruction during coal and gas outburst.[28]

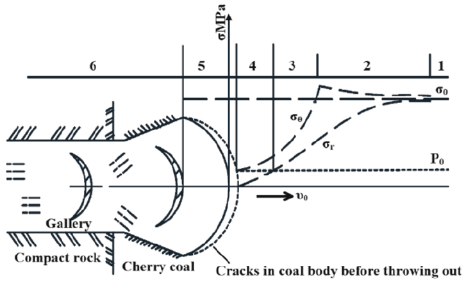


Figure 3. Spherical shell instability theory of coal and gas outbursts. Reprinted from ref 28. Copyright 1995 with permission from Safety in Coal Mines.

Liang and Zhang proposed a coupled solid flow destabilization theory for coal and gas outburst based on the interaction mechanisms between the deformation and failure of the coal and gas seepage. This theory suggests that a coal and gas outburst is caused by the rapid and sudden local failure of gas-bearing coal bodies under the influence of mining activities, which is the result of the combined effect of three main factors: stress, gas, and coal quality, and destabilization will occur only when the energy of the system in its state is not minimal in its nearby domain. The theory is based on the mechanisms of coal rock damage mechanisms, which is a process in which the development of internal cracks and fractures plays a dominant role, and thus destabilization theory can provide a theoretical basis for the technique of forecasting a coal and gas outburst using coal body microrupture information.[29]

The above description describes some research results on the hypothesis of coal and gas outburst mechanisms proposed by domestic and foreign experts and scholars. According to the existing research results, coal and gas outbursts are dynamic processes. The whole process can be divided into four stages: preparation stage, trigger stage, development stage, and termination stage (as shown in Figure 4). With the continuous progress and innovation of science and technology, more and more experts and scholars have started to study the mechanisms and influencing factors of coal and gas outbursts to explain the mechanisms of coal and gas outbursts in a more detailed way, so as to deepen the understanding of the coal and gas outburst phenomenon and provide theoretical guidance for the work of anti-outburst.

3. CURRENT STATUS OF RESEARCH ON HYDRAULIC COAL AND GAS OUTBURST PREVENTION AND CONTROL TECHNOLOGY

For coal seams with the risk of coal and gas outburst, taking hydraulic measures is an effective method to prevent and control coal and gas outbursts. This measure can prevent and control the

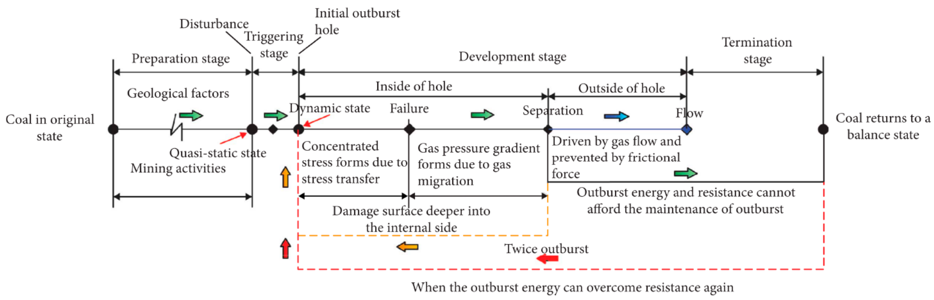


Figure 4. Dynamic stage of the coal and gas outburst. Reprinted from ref 30. Copyright 2021, with permission from Hindawi.

coal and gas outburst by changing the gas, ground stress, and other factors affecting outbursts in the coal rock body. Hydraulic measures generally have two ways to unload pressure and increase the permeability of the coal seam: one is hollowing, using the impact of high-pressure water to hollow, slit, or punch, so as to expand the coal output and provide space for coal seam deformation, specifically including hydraulic slitting, hydraulic hollowing, hydraulic punching, etc.; the other way is fracturing measures, namely, hydraulic fracturing, by injecting high-pressure water into the borehole, fracturing the borehole to form fissures, or making the original fissures expand and extend, so as to achieve the purpose of destroying the coal seam and eliminating outburst and increasing permeability.

3.1. Hydraulic Fracturing Technology. Coal seam hydraulic fracturing technology aims to realize the formation and extension of fracture networks by injecting high-pressure fluids into coal seams. In the process of hydraulic fracturing, by injecting a high-pressure liquid into the borehole, a large number of new cracks are generated inside the coal body. These cracks gradually expand and extend with an increase in the fracturing time, and the amount of fracture damage gradually increases. This damage further causes the cracking, expansion, and extension of secondary cracks, so that the fracturing fluid can enter the secondary cracks.[31,33] Practices and research show that compared with other permeability enhancement techniques, hydraulic fracturing technology has many advantages such as simplicity and ease, cost effectiveness, and practicality. This technology can not only increase the overall permeability of the coal seam but also solve the problem of the overall mechanical properties of coal rock bodies. Therefore, hydraulic fracturing technology has an important application value in low-permeability coal seam mining. Especially in high-gas and low-permeability coal seam mining, it can reduce the probability and risk of coal and gas outbursts, improve the coal seam gas extraction rate, and further increase the coal seam gas extraction. When constructing a hydraulic fracturing system, it is necessary to fully consider the changes of the in situ stress and permeability in the coal seam during high-pressure water injection. Many researchers have studied model construction and experimental verification and designed efficient hydraulic fracturing schemes based on the research results.[34]

After a theoretical analysis, Cao and other scholars constructed a calculation model for the initiation pressure of multilayer coal seams. In order to verify the accuracy of the model, they carried out triaxial hydraulic fracturing simulation experiments to study the influence of the coal seam dip angle and coal seam stress on the initiation pressure and crack extension during hydraulic fracturing. The results show that in multilayer coal seams, the crack initiation position is located in the soft coal seam and extends along the direction of the maximum principal stress. In addition, with the increase of the dip angle of the coal seam, the hydraulic fracture of the multilayer coal seam gradually transitions from a complex fracture network to a single main fracture.[32] Adachi et al. studied the coupling of hydraulic fracturing in three processes, including the mechanical deformation of the fracture surface under fluid pressure, fluid flow in the fracture, and fracture extension.[35] Wang et al. performed a numerical analysis of hydraulic fracturing of nonhomogeneous rock materials and used the simulation results to interpret four stages of hydraulic fracturing: stress concentration, induced cracking, stable crack expansion, and crack closure.[36] Qing et al. conducted a theoretical analysis based on the mechanisms and process of hydraulic fracturing to derive pressure parameters applied to high methane low permeability outburst coal seams, and finally came up with a reasonable water injection pressure equation.[37] Huang et al.[38] used true triaxial hydraulic fracturing experiments combined with numerical simulation to study the effect of coal seam geological characteristics on hydraulic fracturing crack extension and found that under the same stress conditions, the maximum principal stress has a weaker control on hydraulic fracturing crack extension, while the coal seam inclination angle has a greater control on the crack extension, and moreover, the reasonable layout is more conducive to the development and extension of the cracks. Kang et al.[39] used similar materials to simulate coal seams, combined with theoretical analysis and field applications, to study the effect of ground stress on the fracture expansion law of hydraulic fracturing in coal seams (as shown in Figure 5), proposed the optimal arrangement of gas extraction boreholes based on the fracture expansion law under the effect of ground stress, combined hydraulic fracturing and gas extraction according to the characteristics of ground stress and geological structure, and proposed a set of integrated hydraulic fracturing and gas extraction process systems of "selection–judgment–

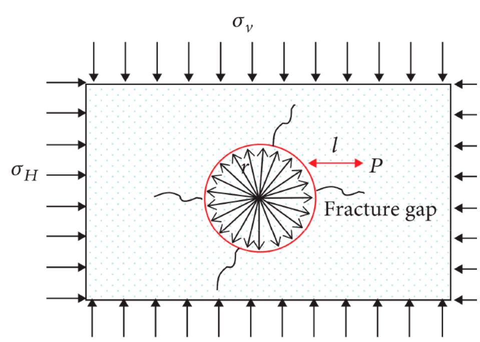


Figure 5. Mechanical model of crack initiation under hydraulic fracturing. Reprinted from ref 90. Copyright 2022, with permission from Hindawi.

https://doi.org/10.1021/acsomega.3c07010
ACS Omega 2023, 8, 44472−44484

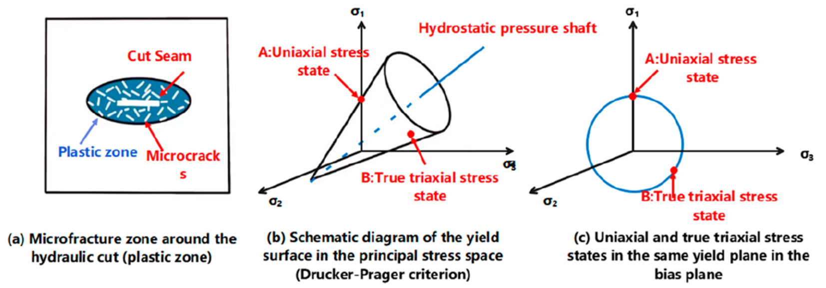


Figure 6. Schematic diagram of microcrack zone (plastic zone) around hydraulic cutting and yield surface inside microcrack zone. Reprinted from ref 45. Copyright 2020, with permission from Journal of Mining & Safety.

fracturing−drilling−extraction" under the effect of ground stress. Meanwhile, Zhao et al.[40] investigated the influence of geological conditions and engineering construction on the effect of composite fracturing and established a three-dimensional hydraulic fracturing model for multilayer composite fracturing to analyze the propagation law of combined fracturing in alternating soft and hard formations, which further confirmed the potential of the future application of composite fracturing technology through the analysis.

In view of the large uncertainty of the risk of coal and gas outburst, the current outburst risk assessment is still mainly based on gas dynamic accident phenomena or empirical indicators of coal and gas outburst, while the question of whether stress perturbation and structural changes to the coal rock body by pressure during hydraulic fracturing will induce outburst has not been fully confirmed; therefore, further observation and confirmation are needed. At present, most of the methods for hydraulic fracturing to prevent coal and gas outbursts are carried out by drilling through the seam. Because the coal body has characteristics such as double pore structure, joint fractures, and large differences in local stress environment, the fracturing effect is greatly influenced by the structure and native fractures of the coal seam, and it is difficult to guarantee the consistency of the fracturing effect. Based on this, simple hydraulic fracturing technology is still in urgent need of further in-depth research in the prevention and control of coal and gas outbursts.

3.2. Hydraulic Slotting Technology. Compared with other hydraulic penetration enhancement technologies, hydraulic slitting technology has the characteristics of effective control of the water jet cutting speed, which can achieve uniform cutting of coal and avoid the problem of unbalanced pressure discharge in the local area due to excessive or insufficient coal hole sections. The advantages of this technology have been extensively studied by several scholars, and related research results have been published.

Yang et al. carried out a study on the seepage law of coal seam during hydraulic slit process; through Matlab simulation software, they derived the changing law of coal seam stress, gas pressure, and gas extraction yield during hydraulic slit process, and the amount of gas extraction was greatly increased compared with the conventional extraction technology.[41] Zhao observed through his study that the way of hydraulic slitting can release part of the effective volume stress within the coal seam,[42] causing part of the seam to collapse after slitting and redistribution of the stress field, which in turn increases the number and length of cracks and fissures as well as the openness within the coal seam, thus increasing the permeability of the low-permeability seam. For the process of hydraulic cutting coal seam and extraction process of drilling data Wang et al.[43] carried out field tests, where hydraulic slit cutting technology changes the gas flow pattern in the coal seam around the drilling hole from a one-way bidirectional radial flow to both radial and axial flows. In addition, the average single-hole gas extraction rate was significantly increased by a factor of 3. In recent years, with the development and renewal of gas extraction technology and equipment, many scholars have carried out theoretical research and field practice on hydraulic slotting technology. Li et al.[44] used a hydraulic fracturing−hydraulic slotting combined antireflection technology in predrainage of coal seam gas, the antireflection principle of technology was analyzed and field tests were carried out, which achieved good results. Liu et al.[45] used the particle flow simulation method (PFC2D) to carry out uniaxial compression numerical simulation tests on coal bodies containing single fractures with different angles and multiple fractures with different spatial arrangements. In view of the physical mechanisms that the development and connectivity of microfractures around hydraulic slotting promote the pressure relief and permeability enhancement of coal seams, it is considered that the micro fracture area around the hydraulic slotting groove can be regarded as the local plastic development of rock, that is, the yield of rock (as shown in Figure 6). In addition, two indexes are proposed to evaluate the effect of pressure relief and permeability enhancement of coal seam slotting: the uniaxial stress threshold and the connectivity of multiple slotting when the microcracks are significantly generated during the loading process.

At the same time, many researchers have studied the ultrahigh-pressure hydraulic slotting technology. Ji et al. selected the Gaohe coal mine as the research object and used the ZGF-100 model device to carry out the integrated operation of high-pressure hydraulic cutting and drilling in the coal seam. The results show that the technology can reduce the workload by 50%, and the single-hole gas flow rate is increased from the original 1.80−3.6 times.[46] This technology is mainly applicable to coal seams with thicker seams, a high gas content, softer coal bodies, and lower permeability. At present, the selection of parameters in field applications mostly relies on past experience and lacks professional theoretical guidance. The traditional hydraulic slitting method is to use a pure water jet with low pressure and high flow rate for cutting, but this method easily triggers water in the working area when applied, and in a drilling slitting operation in a deep high-gas and low-permeability coal seam, a collapse phenomenon can easily occur, which affects the length of the formed hole and the effect of suppressing coal and gas outburst. Hence, it is necessary to solve the related engineering problems, such as drainage, slag discharge, and extraction collapse hole, in order to obtain better effects of coal and gas outburst control.

3.3. Hydraulic Punching Technology. China is one of the major coal mining countries in the world and one of the earliest countries to carry out the research and application of hydraulic punching technology. This technology aims to protect the coal and gas outburst as a safety barrier by using high-pressure water to impact and destroy the protruding coal seam construction borehole with self-jetting ability using high-pressure water to impact and destroy the coal body around the borehole in the hole, so as to induce and control the jet hole and form a cavity. Through this process, the surrounding coal body is radially displaced under the action of ground stress and gas pressure; the stress distribution around the borehole changes, cracks are formed, and the permeability of the coal seam increases. In addition, the coal around the borehole is wetted, its elasticity decreases, and its plasticity increases, which effectively increases the length of the overpressure relief zone at the working face and reduces the coal and gas outburst potential of the coal seam.[48] Through extraction, the coal seam gas pressure and gas content can be effectively reduced to achieve the purpose of preventing and controlling coal and gas outbursts.

Since the 1980s, hydraulic perforation technology has been applied on a large scale in the field of coal bed methane development in the San Juan Basin of the United States and achieved good results.[47] Wang and other scholars studied hydraulic punching measures to increase permeability for the characteristics of a loose and poorly permeable coal seam in Luobian coal mine in Jiahe County and found that hydraulic punching was effective in the process of pumping and abating coal and gas outbursts in the area of loose and low-permeability coal seams.[49] Wei and other scholars established the gas−solid coupling equation of hydraulic perforation in a coal seam bottom lane based on the relationship among a mechanical equilibrium equation, mass conservation law, and parameters such as coal seam permeability, porosity, and coal rock volume strain and successfully simulated the change trend of the effective radius of hydraulic perforation under different coal discharge conditions, and the results showed that the effective radius of hydraulic perforation increased gradually with the increase of coal discharge and extraction time.[50] Currently, research scholars pay more attention to the method of combining theoretical analysis with field tests to explore in depth the application of hydraulic punching technology in preventing and controlling coal mine accidents. Wang and other scholars used COMSOL Multiphysics field numerical simulation software to simulate the effect of hydraulic flushing in coal seams on gas extraction, analyze the stress distribution around the borehole before and after hydraulic flushing (as shown in Figure 7),[51] and after comparing with the actual situation in the field, determine the reasonable coal output of hydraulic flushing as 0.7 t/m and further determine the reasonable coal output of hydraulic flushing and the effective range gradient law and the logarithmic relationship between the influence radius of hydraulic punching and mining time. Xu[52] and other scholars, on the other hand, used a combination of field tests and numerical simulations to analyze and study the effects of different coal output and different mining periods on the effective mining radius, using Zhong Macun coal mine as an example, and the increase in coal production can improve the effective mining radius of the borehole. In the hydraulic punching test in Zhaozhuang mine, Zhang[53] and other scholars compared the field application effects of different hydraulic punching processes, monitored and analyzed the relationship between the water content of coal around the borehole blockage and the gas extraction effect, and concluded that the occurrence of borehole blockage was the result of the combined effect of cinder particle size and punching back water discharge capacity.

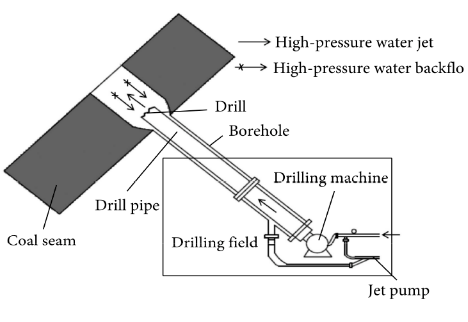


Figure 7. Schematic diagram of hydraulic punching equipment and technical process. Reprinted from ref 52. Copyright 2020, with permission from Hindawi.

In addition, researchers and scholars have proposed different hydraulic punching measures for different coal seams. Hydraulic punching cavitation technology is a technology mainly used to enhance the permeability of a soft coal seam. By formation of a large area of karst cave in the coal seam, the coal seam is relieved to a greater extent, and the ground stress is released to avoid the occurrence of coal and gas outburst accidents. Wang et al.[54] carried out research on hydraulic punching cavitation, analyzed the pressure release mechanism and the stress path around the cavitation cavity through theoretical analysis, numerical simulation, experimental verification, and other research methods, and found that the hydraulic punching cavitation can significantly increase the maximum radius of the plastic damage zone and that the effect of pressure relief is more obvious. It is found that hydraulic punching cavitation can significantly increase the maximum radius of the plastic damage zone and the effect of coal seam pressure relief is more obvious. Gu et al.[55] proposed hydraulic punching pressure relief and deviation prevention technology for Lugou coal mine and used FLAC three-dimensional software to construct relevant mathematical models to compare the change law of failure radius under different coal output conditions and the ratio change law of hydraulic punching extraction concentration and ordinary borehole gas extraction concentration under different coal output conditions. At the same time, Xu specially used a new type of outburst prevention technology of hydraulic punching and air blasting for a low-permeability soft coal seam. The LS-DYNA simulation software was used to simulate the blasting process and analyze the change of gas drainage volume at different blasting times.[56] In summary, hydraulic punching can make the coal seam get sufficient pressure relief, promote gas desorption and emission, and prevent the occurrence of coal and gas outburst accidents, but the punching equipment and process need further research to improve its integration and ease of use.

4. CURRENT STATUS OF RESEARCH ON ANHYDROUS COAL AND GAS OUTBURST PREVENTION AND CONTROL TECHNOLOGY

Among the measures to prevent and control coal and gas outburst accidents in low-permeability coal seams, hydraulic anti-outburst technology is a widely adopted measure, which has advantages such as a significant fracture-causing effect and relatively low water resources cost, but also faces serious problems of the water lock effect. Considering that in areas

https://doi.org/10.1021/acsomega.3c07010
ACS Omega 2023, 8, 44472−44484

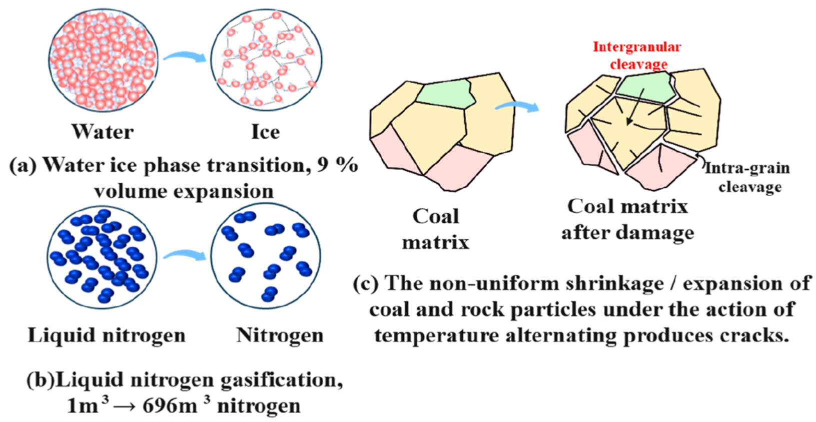


Figure 8. Mechanisms of liquid nitrogen cold impact cracking. Reprinted from ref 72. Copyright 2021, with permission from Bulletin of National Natural Science Foundation of China.

where water is scarce hydraulic technology is no longer applicable, another measure needs to be found to prevent the occurrence of coal and gas outburst accidents. In recent years, some research scholars have tried to inject cryogenic fluids, such as liquid carbon dioxide and liquid nitrogen, into materials such as coal rocks and sandstones to achieve the effect of cold cracking rocks by using their low-temperature phase change expansion. Compared with hydraulic technology, anhydrous cold fracturing technology has the advantages of more water conservation and less impact on environmental pollution, and so it is expected to become a potential application technology in the field of coal and gas outburst accident prevention and control.

4.1. Liquid Nitrogen Fracturing Technology. Liquid nitrogen fracturing technology is the use of liquid nitrogen as a fracturing fluid to fracture coal seams to achieve the purpose of improving coal reservoir permeability, enhancing gas extraction rate, and avoiding coal and gas outburst accidents, and its cold flush fracturing mechanisms are shown in Figure 8. During liquid nitrogen fracturing, the rock under downhole conditions will be subjected to severe thermal stresses due to the unique low-temperature properties of liquid nitrogen. As a result, not only multiple primary fractures but also secondary fractures perpendicular to the primary fractures will be formed in the reservoir, thus shaping a more complex fracture network than traditional hydraulic fracturing.[57] At the same time, since water and solid particles do not exist in the fracturing process, it can avoid water-sensitive and water-locked injuries caused by a water-containing fracturing fluid as well as prevent solid particles from blocking pores and fractures and reducing the permeability of coal seams. Liquid nitrogen fracturing technology originated in the United States, and as early as 1971, Allen and Bauer[58] recognized that injecting frozen fluids (liquid nitrogen, low-temperature brine, etc.) into rock fractures can achieve increased production; in 1997, McDaniel et al.[59] successfully demonstrated the good effect of this technology in coalbed methane extraction through field tests. Since the coalbed methane extraction technology in the United States could meet market demand in the late 1990s, this technology was not further studied until the increase in demand for coalbed methane in recent years, which caused liquid nitrogen fracturing technology to re-emerge as a research focus for domestic and foreign scholars.[60]

Cong and other research scholars revealed the mechanism of liquid nitrogen fracturing by studying the changes in temperature and stress field before and after injection of liquid nitrogen into the borehole and derived the equation of the thermal expansion coefficient of coal and the change rule of radial thermal stress under temperature and stress field.[61] Akhondzadeh et al. studied the structural changes of the fracture by liquid nitrogen fracturing, used 3D X-ray microcomputed tomography to observe the fracture before and after liquid nitrogen fracturing in bituminous coal, and found that the porosity of the coal seam increased by more than 11% and that the fracture extension was connected with other fractures, thus increasing the connectivity and permeability of the coal seam.[62] The effect of liquid nitrogen fracturing is different for different types of coal. Nikolenko et al.[63] studied the effect of liquid nitrogen fracturing on different types of coal samples and proposed a new detection technology to study the formation process of cracks. The results showed that there was an inverse correlation between the degree of original metamorphism of the coal samples and the quality of crack development.

Domestic researchers and scholars have also carried out research on liquid nitrogen fracturing technology. Zhang and others carried out a series of studies on this basis, mainly including the establishment of a mathematical model of water injection wetting in boreholes and a model of cold fracture permeability increase in borehole coal injected with liquid nitrogen, which were used to calculate the injection time, wetting radius, and analytical solution of temperature field evolution of a coal seam frozen with liquid nitrogen and the radius of cold fracture permeability increase in coal seam injected with liquid nitrogen, respectively; the response of anthracite and coking coal under liquid nitrogen freezing fracture was investigated, and it was found that the degree of damage of dry coal samples was more severe than that of coking coal after liquid nitrogen.[64−67] In addition, by testing the changes in sound velocity, representative fracture area, and surface microstructure of coal samples before and after liquid nitrogen immersion, we further deduced the freezing and swelling pressure of the water phase into ice in the water-saturated fracture under the action of liquid nitrogen. The mechanical criterion for the extension of fractured coal in water-saturated coal under liquid nitrogen leaching was also constructed.

In recent years, many scholars have carried out research on liquid nitrogen fracturing technology from different perspectives. Su[69] and other scholars carried out a series of experimental studies from different perspectives based on the introduction of fractal theory, and the results showed that the compressive strength and modulus of elasticity of the coal samples were reduced, and the fractal dimension was reduced after treatment with liquid nitrogen. Hou et al.[68] also studied the mechanical properties of coals before and after liquid nitrogen fracturing and divided the whole process of penetration enhancement into three stages: the initial state, the freezing state, and the freezing−thawing state. The mechanical properties of coal samples in the freezing stage and freezing−thawing stage are opposite. At the same time, it was found that the crack development in the thawing process was better than that in the freezing process and the crack growth rate was faster. Liu et al.[70] selected different types of coal samples for liquid nitrogen cold soaking and NMR experiments, and concluded that the best penetration-enhancing effect was for anthracite, the worst was for lignite, and the fracturing effect was better with the increase of the number of cold soakings. Zhai[71,72] proposed a low-temperature cycling fracturing and permeability enhancement method to address the difficulty of gas extraction from conventional boreholes of single low permeability coal seams in China and conducted a total of 20 cycles of freeze−thaw tests on water-saturated coal samples using a freeze−thaw machine to analyze the evolution of pore structure characteristics of coal bodies under the effect of low-temperature cycling freeze−thaw; the results showed that the percentage of medium and large pores, total porosity, effective porosity, and permeability of coal samples increased significantly with the increase of freeze−thaw times, which led to a significant enhancement of coal permeability. At the same time, Longinos and other scholars studied the effect of freezing time and freezing cycle times on the effect of liquid nitrogen fracturing. It was found that the uniaxial compressive strength of the freezing time experiment was greater than that of the freezing cycle times experiment, whether it was dry or water-saturated samples.[73]

According to the current research results, most of the scholars have focused on the study of the fracture structure, number, and extension direction of the coal body before and after liquid nitrogen fracturing, and there have been fewer studies on the mechanism of liquid nitrogen fracturing. At the same time, most of the research on the main factors affecting the effect of liquid nitrogen fracturing has been carried out through the method of controlling variables on a single influencing factor, ignoring the interaction between various influencing factors. At present, the practical application of liquid nitrogen fracturing technology at home and abroad is relatively small, and it is still necessary to improve the relevant process and develop efficient and convenient mechanical equipment. Therefore, future research should focus on these aspects in order to understand the mechanisms of liquid nitrogen fracturing technology in a more comprehensive and in-depth manner.

4.2. Liquid CO_2 Fracturing Technology. In recent years, the liquid CO_2 coal seam fracturing and permeability increasing technology has significantly improved the gas extraction efficiency of low-permeability coal seams and prevented the occurrence of coal and gas outburst accidents.[74] The technology was initially used in the development of oil and gas wells but has been widely used in the coal industry in recent years. The principle of carbon dioxide phase transition technology is to use the transition from a liquid to a gaseous state to produce instantaneous gasification expansion, resulting in high pressure and shear flakes and releasing high-pressure gas from the explosion port. After the injection of liquid CO_2, the internal temperature of the coal body drops sharply, and then the thermal stress cracks caused by different shrinkage deformations of the matrix are generated.[75,76] Compared with other technologies, this technology does not require the use of water, can effectively avoid environmental pollution, and has the advantages of nonsparking, easy pressure control, easy storage and transportation, and high safety. With the deepening of coal seam mining and the increasing requirements for mining technology, more and more scholars have started to conduct in-depth research on liquid CO_2 fracturing technology (as shown in Figure 9).

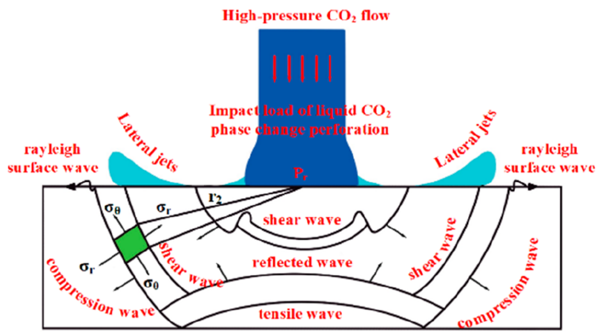


Figure 9. Mechanical mechanisms of liquid CO_2 phase change perforation and fracture propagation in low-permeability coal seams. Reprinted from ref 87. Copyright 2018, with permission from Journal of China Coal Society.

Liao[77] observed the structural changes of the coal samples before and after the treatment from a microscopic point of view and found that many new microfissures appeared on the surface of the treated coal samples and that the fissures were interconnected with each other, which greatly improved the range of gas transportation and the permeability of the coal seam. Wen[78] used a mercuric pressure meter and X-ray computed tomography equipment to determine the pore changes in coal seams and found that the total pore volume, total pore area, average pore diameter, and gas seepage channels of coal samples were increased after a CO_2 freeze−thaw treatment. Liu et al.[79] mainly investigated the changes of medium pores and micropores in coal samples and found that liquid CO_2 fracturing had obvious effects on medium pores but had almost no effect on micropores, many semiclosed pores were converted to open pores, and the connectivity between medium pores was enhanced. Meanwhile, Liu[80] and Xia[81] introduced fractal theory to analyze the change of pore structure before and after the coal body, and the fractal dimensions of the coal samples were all significantly reduced after fracturing, which indicated that the roughness and inhomogeneity of the pores of the coal samples were reduced. Besides, some scholars analyzed the changes before and after coal body treatment from the perspective of numerical simulation. Yu and other scholars constructed a coal seam fracture expansion and deformation model, a gas diffusion model, and a coal seam permeability change model and analyzed the effects of hole spacing, fracturing method, gas pressure, and other influencing factors on the fracturing effect of liquid CO_2 by controlling variables and then came up with the optimal fracturing method in Wangjialing coal mine. Different coal mines have different geological conditions, and the most suitable fracturing method should be selected according to the actual conditions of the coal body.[82]

Some scholars have also studied the main factors influencing the liquid CO_2 phase transition fracture. Wang et al.[83−86] studied the TNT equivalent of liquid CO_2 phase change fracturing, so as to determine the radius of influence of liquid

https://doi.org/10.1021/acsomega.3c07010
ACS Omega 2023, 8, 44472−44484

CO_2 phase change fracturing blasting and reasonable charge quantity and deployment parameters; by adopting a liquid CO_2 phase change fracturing technology for a single low-permeability coal seam, it was found that instantaneous high-pressure CO_2 gas impacted the coal body and produced a large number of fractures. In order to better apply the liquid CO_2 phase change fracturing technology to the field of low-permeability coal seam permeability enhancement and reinforced anti-outburst field, a field test of liquid CO_2 phase change fracturing for enhanced prepumping coal seam gas through the seam was conducted in the 13th mine of Pingjiang coal mine and through the gas extraction effect after fracturing the coal seam to determine the reasonable placement of liquid CO_2 blasting holes. Jia et al.[88] used LS-DYNA software to simulate and analyze the effects of physical parameters of coal seams and borehole diameter on the effect of liquid CO_2 phase change fracturing on coal seams, and the results show that there are positive relationships between the fracturing effect of coal seams and the pressure, modulus of elasticity, and borehole diameter, there are negative relationships with the geopathic stress and compressive strength, and the process is nearly irrelevant to the tensile strength. Hu et al.[89] tablished a multiphysical field coupling model and found that the longer the liquid CO_2 phase transition cracking time, the greater the fracturing radius. After the fracturing, the fracturing radius remained almost unchanged, and the greater the gas pressure, the more significant the increase in the coal seam permeability.

The phase change fracturing technology of liquid CO_2 has received much attention in the field of high-gas and low-permeability coal seam penetration in China, but the current research results have focused more on the fracture extraction effect and extraction radius of this technology, while in-depth research on the mechanisms of phase change fracturing, fracture process, fracture morphology changes, and main influencing factors is still relatively scarce. Therefore, further research on this technology and related mechanisms is needed to better guide engineering practice and promote its application in actual production.

5. PROBLEMS AND DEVELOPMENT TREND OF HYDRAULIC AND NONHYDRATION COAL AND GAS OUTBURST PREVENTION AND CONTROL TECHNOLOGY

5.1. Problems in Hydraulic and Nonhydration Coal and Gas Outburst Prevention and Control Technology. A number of domestic research institutions have conducted research on hydraulic and anhydrous technologies, which have promoted the rapid development of these two types of technologies and achieved preliminary results in some coal mines. However, the complexity, specificity, and mutability of deep coal seam gas power disasters have put forward higher requirements for these two technologies. At present, hydraulic and anhydrous technologies still have not formed a perfect and effective technical system, and synergy is not enough to adapt to complex changes in mining conditions; the following problems mainly exist.

(1) In-depth research on the mechanisms of coal and gas outburst is a difficult problem that needs to be solved at present. Scholars at home and abroad have made fruitful research results on the mechanisms of coal and gas outburst, but most of them are simplified analyses of the comprehensive hypothesis, and the conditions of coal and gas outburst, influencing factors, and the development and evolution process still require more in-depth and detailed research.

(2) The understanding of mechanisms of the hydraulic measures is not deep. At present, there are pressure-boosting and pressure-relief measures in hydraulic technology, and there are no accurate research data on the stress state inside the coal seam before and after the implementation of different measures, as well as the law of gas desorption and transportation, so it is impossible to study in depth the mechanisms of the hydraulic measures to eliminate coal and gas outburst.

(3) The application of different hydration technologies is not clear. Hydraulic technology applicable conditions cannot quantify the applicable boundary conditions of different hydraulic technologies, resulting in blindness in the hydraulic technology of engineering applications, and therefore there is a perfect specification system.

(4) The application of liquid nitrogen fracturing technology in the study of fracturing of low-permeability coal seams is limited, and the current research direction has mainly focused on macroscopic fracture and overall structural damage law under a single cycle of liquid nitrogen, while there have been few studies on surface microscopic fractures, pore structure, and the mechanisms of liquid nitrogen fracturing.

(5) There have been few studies on the factors influencing the effect of CO_2 phase change in liquid CO_2 fracturing technology. In order to better apply this technology to actual production and guide engineering practice, in-depth research on its fracturing mechanisms, fracturing process, fracture morphology changes, and main influencing factors is needed.

(6) The existing measures for unloading pressure and increasing penetration can hardly meet the requirements of intelligent mining. The harsh operating environment and dangerous mining conditions in China's coal mines have led to a greater demand for intelligent operation of coal mining. With the continuous development of digitalization, information technology, intelligent technology, and the deep integration of advanced manufacturing equipment technology and coal mining, the realization of intelligent unmanned mining in coal mines has become a feasible solution.

5.2. Development Trends of Hydraulic and Nonhydration Coal and Gas Outburst Prevention and Control Technology. According to the current problems of coal and gas outburst hydration control technology, future development trends are proposed as follows.

(1) For the problem of coal and gas outburst, further research on the relevant mechanisms is needed. This includes the study of the conditions under which coal and gas outburst occurs and the influencing factors and the occurrence, development, and evolution process of coal and gas outbursts. In the research process, the physical and mechanical properties of coal, ground stress, gas, temperature, and outburst should be studied as a whole to clarify the mechanisms of each factor in the outburst. In order to cope with the characteristics of deep coal rocks, it is necessary to develop coal and gas outburst simulation devices of large size and volume and to carry out quantitative simulation analyses of coal and gas outburst

https://doi.org/10.1021/acsomega.3c07010
ACS Omega 2023, 8, 44472−44484

phenomena in different coal qualities and different mining areas by considering various influencing factors in the process of geological structure, ground stress, coal body strength, gas content, and construction.

(2) The applicable conditions of different hydraulic prevention and control technologies need to be more clear. The most suitable antireflection measures should be selected for mining areas with different geological conditions to increase the permeability of coal seams, avoid the occurrence of coal and gas outburst accidents, and improve the safety and stability of coal mining.

(3) In order to promote the sustainable development of smart mines and intelligent coal mining workings, it is necessary to carry out research on intelligent hydraulic pressure relief and penetration enhancement technology and its equipment. With the continuous development of digitalization, information technology, intelligent technology, and advanced manufacturing technology, intelligent hydraulic pressure relief and augmentation technology has become a feasible solution. For coal and gas outburst coal seams, the development of intelligent drilling rigs, which can realize unmanned and intelligent construction of various drilling holes, will become an important technology. At the same time, it is necessary to develop new pressure relief and penetration enhancement technology or improve the existing hydraulic coal seam pressure relief and penetration enhancement measures to realize unmanned and intelligent pressure relief and penetration. This will help shorten the time of gas hazard management and meet the demand of smart mine and intelligent mining.

(4) Technological innovation needs to be strengthened to explore new fracturing processes and permeation enhancement mechanisms to improve the reliability of technology and permeation enhancement effects. In the future, more efficient, stable, and safe liquid nitrogen fracturing equipment needs to be developed to meet practical application requirements. The application of liquid nitrogen fracturing technology will become more and more digital and intelligent in the future. Based on data collected during the fracturing process of liquid nitrogen, the relationship between fracturing effect and penetration enhancement effect can be analyzed to provide guidance for the optimization of process and equipment. In addition, with the increasing awareness of environmental protection, the future liquid nitrogen fracturing technology also needs to pay more attention to the protection of the environment.

(5) There should be strengthened core technology innovation, reduction of costs, and development of more efficient and reliable liquid CO_2 fracturing equipment and processes. Meanwhile, there should be an enhancement of the maturity of liquid CO_2 fracturing technology and further improvement of process flow and equipment performance to reduce the frequency of equipment maintenance and overhaul and improvement in efficiency. The future liquid CO_2 fracturing technology needs to pay more attention to environmental protection, develop environmentally friendly CO_2 fracturing agents and equipment, reduce CO_2 emissions, and reduce the negative impact on the environment.

(6) The construction of intelligent mines will develop toward unmanned or less humanized operations. Onombining intelligent mining technology, sensor intelligent perception technology, information and communication technology, and intelligent decision-making and control technology, the visualization and intelligent processing of mine production processes and the production environment can be realized, and the safety and sustainability of mine mining can be improved.

6. CONCLUSION

This review discusses the research history of coal and gas outburst mechanisms and lists several mainstream hypotheses. The main hydraulic measures are listed in detail as hydraulic fracturing, hydraulic slitting, and hydraulic perforation as are the main anhydrous control technologies of liquid nitrogen fracturing technology and liquid CO_2 fracturing technology. Based on the introduction of the principle of action, development history, and practical tests of each, the advantages, disadvantages, and application scope of each technology are analyzed. We further summarize the problems of coal and gas outburst hydration and anhydrous prevention and control technology in practical application and propose improvement measures for these problems. The coal and gas outburst hydration prevention and control technology needs to promote the application of intelligent and digital technology, develop more efficient, stable, and safer hydration equipment, and at the same time strengthen the awareness of environmental protection and reduce the adverse impact on the environment. The coal and gas outburst anhydrous prevention and control technology needs to strengthen the research and development of the core technology, explore new fracturing processes and permeation mechanisms, improve the reliability and permeation effect of the technology, and also pay attention to the impact of the technology on the environment when it is actually applied and develop environmentally friendly fracturing agents and equipment.

■ AUTHOR INFORMATION

Corresponding Author

Liguo Wang − *Henan Polytechnic University, Jiaozuo, Henan 454000, People's Republic of China; Engineering Research Center of Coal Mine Disaster Prevention and Emergency Rescue, Ministry of Education, Henan Polytechnic University, Jiaozuo 454000, People's Republic of China; Collaborative Innovation Center of Coal Work Safety and Clean High Efficiency Utilization, Jiaozuo, Henan 454000, People's Republic of China*; Email: wangliguofirst@126.com

Authors

Jifen Zhang − *Henan Polytechnic University, Jiaozuo, Henan 454000, People's Republic of China*; orcid.org/0009-0007-1715-3934

Xiangjun Chen − *Henan Polytechnic University, Jiaozuo, Henan 454000, People's Republic of China; Engineering Research Center of Coal Mine Disaster Prevention and Emergency Rescue, Ministry of Education, Henan Polytechnic University, Jiaozuo 454000, People's Republic of China; Collaborative Innovation Center of Coal Work Safety and Clean High Efficiency Utilization, Jiaozuo, Henan 454000, People's Republic of China*; orcid.org/0000-0003-4849-8349

Complete contact information is available at: https://pubs.acs.org/10.1021/acsomega.3c07010

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

The authors the anonymous reviewers for their valuable suggestions. The authors also express their appreciation of the funding provided by the National Natural Science Foundation of China (Nos. 52174172, 52074107) and the Henan Provincial Science and Technology Research Project (No. 232102320234).

REFERENCES

(1) National Bureau of Statistics. *Statistical Bulletin of the People's Republic of China on National Economic and Social Development*, 2022.

(2) Black, D. J. Review of coal and gas outburst in Australian underground coal mines. *International Journal of Mining Science and Technology* **2019**, *29* (06), 815–824.

(3) Hudecek, V. Analysis of safety precautions for coal and gas outburst-hazardous strata. *Journal of Mining Science* **2008**, *44* (5), 464–72.

(4) Zhang, C. L.; Wang, P. Z.; Wang, E. Y.; Xu, J.; Li, Z. H.; Liu, X. F.; Peng, S. J. Coal and gas outburst mechanisms: Research progress and prospect in China over the past 70 years. *Coal Geology & Exploration* **2023**, *51* (02), 59–94.

(5) Hou, G. Analysis and research on system function and typical mode for intelligent mining in coal mine. *China Coal* **2022**, *48* (02), 55–60.

(6) Li, Q. G.; Zhao, Z. D.; Liu, P.; Nie, B. S.; Zhao, Y. L.; Liu, X. F.; Deng, B. Z.; Wang, M. J. Evaluation of structural damage and gas transportability change in coal subjected to ultrasound stimulation using image-based modeling and permeability tests. *Fuel* **2023**, *349*, 349–128684.

(7) Liu, Y. L.; Zheng, X. B.; Peng, X. F.; Zhang, Y. Y.; Chen, H. D.; He, J. H. Influence of natural fractures on propagation of hydraulic fractures in tight reservoirs during hydraulic fracturing. *Marine and Petroleum Geology* **2022**, *138*, 105505.

(8) Yang, W.; Lin, B. Q.; Gao, Y. B.; Lv, Y. C.; Wang, Y. K.; Mao, X. B.; Wang, N. B.; Wang, D.; Wang, Y. J. Optimal coal discharge of hydraulic cutting inside coal seams for stimulating gas production: a case study in pingmei coalfield. *Journal of Natural Gas Science and Engineering* **2016**, *28*, 379–388.

(9) Fan, C. J.; Yang, L.; Li, S.; Sun, H.; Luo, M. K.; Zhou, L. J.; Yang, Z. H.; Li, S. Recent Advances and Perspectives of CO_2-Enhanced Coalbed Methane Experimental, Modeling, and Technological Development. *Energy Fuels* **2023**, *37*, 3371–3412.

(10) Hou, P.; Xue, Y.; Gao, F.; Dou, F. K.; Su, S. J.; Cai, C. Z.; Zhu, C. H. Effect of liquid nitrogen cooling on mechanical characteristics and fracture morphology of layer coal under Brazilian splitting test. *International Journal of Rock Mechanics and Mining Sciences* **2022**, *151*, 105026.

(11) Ha, S. J.; Kim, Y.; Yun, T. S. Development of microcracks in granitic rock by liquid co_2 fracturing. *International Journal of Rock Mechanics and Mining Sciences* **2021**, *146*, 104876.

(12) Cao, Y. L. Research Status and Prospect of Coal and Gas Outburst Prevention and Control by Hydraulic Technology. *Safety in Coal Mines* **2020**, *51* (10), 60–66.

(13) Han, Y.; LV, S.; Zhang, F. Y.; Do, B. W. Research progress and prospect of coal and gas outburst simulation experiments. *Journal of Henan Polytechnic University (Natural Science)* **2022**, *41* (01), 1–8.

(14) Fan, C. J.; Xu, L. G.; Elsworth, D.; Luo, M. K.; Liu, T.; Li, S.; Zhou, L. J.; Su, W. W. Spatial–Temporal Evolution and Countermeasures for Coal and Gas Outbursts Represented as a Dynamic System. *Rock Mech Rock Eng.* **2023**, *56*, 6855–6877.

(15) Lama, R. D.; Bodziony, J. Management of outburst in underground coal mines. *International Journal of Coal Geology* **1998**, *35*, 83–115.

(16) Shepherd, J.; Rixon, L. K.; Griffiths, L. Outbursts and geological structures in coal mines: a review. *International Journal of Rock Mechanics and Mining Science & Geomechanics Abstracts* **1981**, *18* (4), 267–283.

(17) Ma, Y. K.; Nie, B. S.; He, X. Q.; Li, X. C.; Meng, J. Q.; Song, D. Z. Mechanism investigation on coal and gas outburst: An overview. *International Journal of Minerals, Metallurgy and Materials* **2020**, *27* (7), 872.

(18) Paterson, L. A model for outbursts in coal. *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts* **1986**, *23* (4), 327.

(19) Singh, J. G. A mechanism of outbursts of coal and gas. *Mining Science and Technology* **1984**, *1* (4), 269.

(20) Nekrasovski, Y. E. Mining of coal seams liable to outbursts of gas and coal. *Ugletekhizdat, Moscow (in Russian)*, **1951**.

(21) Ma, N. J.; Zhao, X. D.; Zhao, Z. Q.; Liu, H. T.; Jia, H. S. Conjecture about mechanisms of butterfly-shape coal and gas outburst in excavation roadway. *Journal of Mining Science and Technology* **2017**, *2* (02), 137–149.

(22) Ma, Y.-k.; Nie, B.-s.; He, X.-q.; Li, X.-c.; Meng, J.-q.; Song, D.-z. Mechanism investigation on coal and gas outburst: An overview. *International Journal of Minerals, Metallurgy and Materials* **2020**, *27* (7), 872–887.

(23) Wang, H. P.; Zang, Q. H.; Yuan, L.; Xue, J. H.; Li, Q. H.; Zhang, B. Coal and gas outburst simulation system based on CSIRO model. *Chinese Journal of Rock Mechanics and Engineering* **2015**, *34* (11), 2301–2308.

(24) Li, G. R.; Luo, X. R.; Zheng, Y. K.; Wu, D. J. Research status and new ideas of coal and gas outburst mechanisms. *Energy Technology and Management* **2010**, No. 01, 21–23.

(25) Yu, B. F. Discussion on mechanisms of coal and gas outburst. *Coal Science and Technology* **1979**, No. 08, 34–42.

(26) Li, P. F. Discussion on the hypothesis of coal and gas outburst mechanisms-two-phase fluid hypothesis. *Safety in Coal Mines* **1989**, No. 11, 29-35-19.

(27) Zhou, S. N.; He, X. Q. Rheological hypothesis of coal and gas outburst mechanisms. *Journal of China University of Mining & Technology* **1990**, No. 02, 4–11.

(28) Jiang, C. L.; Yu, Q. X. Spherical shell instability hypothesis of coal and gas outburst mechanisms. *Safety in Coal Mines* **1995**, No. 02, 17–25.

(29) Liang, B.; Zhang, M. T.; Pan, Y. S.; Wang, L. G. Solid-fluid coupling instability theory of coal and gas outburst. *Journal of China Coal Society* **1995**, No. 05, 492–496.

(30) Tu, Q.; Cheng, Y. P.; Xue, S.; Ren, T.; Cheng, X. Analysis of the coal and gas outburst mechanism from the perspective of tectonic movement. *Geofluids* **2021**, *2021*, 1.

(31) Liangwei, L.; Wenbin, W. Variation law of roof stress and permeability enhancement effect of repeated hydraulic fracturing in low-permeability coal seam. *Energy Sci. Eng.* **2021**, *9*, 1501–1516.

(32) Cao, S. R.; Li, X. Y.; Zhou, Z.; Wang, Y. W.; Ding, H. Investigation of hydraulic fracturing crack propagation behavior in multi-layered coal seams. *Applied Sciences* **2020**, *10* (3), 1153.

(33) Behnoudfar, P.; Asadi, B. M.; Gholilou, A.; Zendehboudi, S. *A new model to conduct hydraulic fracture design in coalbed methane reservoirs by incorporating stress variations* **2019**, *174*, 1208–1222.

(34) Liu, P.; Fan, L.; Li, Q. G.; Zhong, F. Power ultrasound assisted coalbed methane enhancement recovery: field application and performance evaluation in underground coal mine. *Fuel* **2022**, *324*, 124575.

(35) Adachi, J. I.; Siebrits, E.; Peirce, A. P.; Desroches, J. Computer simulation of hydraulic fractures. *International Journal of Rock Mechanics and Mining Sciences* **2007**, *44* (5), 739–757.

(36) Wang, S. Y.; Sun, L.; Au, A. S. K.; Yang, T. H.; Tang, C. A. 2D-numerical analysis of hydraulic fracturing in heterogeneous geo-materials. *Construction and Building Materials* **2009**, *23*, 2196–2206.

(37) Qing, Y.; Zhenzhen, J.; Baiquan, L.; Jianxin, L.; Guoqi, L. Theoretical Analysis and Practical Study on Reasonable Water Pressure of Hydro-fracturing. *Procedia Engineering* **2011**, *26*, 1361–1369.

(38) Huang, L. S.; Li, B.; Wang, B.; Zhang, J. X. Effects of coal bedding dip angle on hydraulic fracturing crack propagation. *Geomechanics and Geophysics for Geo-Energy and Geo-Resources* **2023**, *9*, 30.

(39) Kang, X. T. *Research on Hydraulic Fracturing Propagation Rules in Coal Seam and Gas Extraction Drilling Optimization*; Chongqing University: 2014.

(40) Zhao, H. F.; Wang, X. H.; Liu, Z. Y.; Yan, Y. J.; Yang, H. X. Investigation on the hydraulic fracture propagation of multilayers-commingled fracturing in coal measures. *J. Pet. Sci. Eng.* **2018**, *167*, 774−784.

(41) Yang, X. L.; Zhang, Y. L.; Ren, Z. C. The Numerical Simulation for Seepage Rule of Coal-Bed Methane with Hydraulic Cutting Seam Mining Based on Matlab. *Advanced Materials Research* **2012**, *524-527*, 485.

(42) Zhao, L.; Feng, Z. C.; Yang, D.; Zhao, Y. S. Testing Study of Improving Seepage flow Laws of Low seepage Coalbed by Hydratic-cutting Seams. *Journal of Taiyuan University of Technology* **2001**, No. 02, 109−111.

(43) Wang, X. Study on technology of hydraulic cutting seam of ultra-high pressure with strip predrilling. *IOP Conference Series: Earth and Environmental Science* **2019**, *358*, 052047.

(44) Li, Z. F.; Sun, D. F.; Chen, J. F.; Lei, H. B.; Xiao, S. Q. Application of permeability improving technology combined with hydraulic pressure fracturing and hydraulic slotting. *Coal Science and Technology* **2015**, *43* (10), 72−76.

(45) Liu, S. L.; Zhu, C. J.; Lin, B. Q.; Liu, T. The effect of spatial distribution mode of hydraulic slotting on pressure relief and permeability enhancement of the coal seam. *Journal of Mining & Safety Engineering* **2020**, *37* (05), 983−990.

(46) Lu, Z. J.; Ji, F. Experimental study on ultra high pressure hydraulic cutting seam pressure relief and permeability enhancement of strip drilling along seam in C19 coal seam of Shi Ping No.1 Coal Mine. *IOP Conference Series: Earth and Environmental Science* **2021**, *804*, 022040.

(47) Duan, M. X.; Gao, D. L.; Zhang, H.; Wang, D. G. Research on Dynamics Mechanical of Air-force Cave Completion in Coalbed Methane Well [C]// China Coal Society Coalbed Methane Professional Committee, China Petroleum Society Petroleum Geology Professional Committee. *Coalbed Methane Academic Seminar Papers*; Geological Publishing House: 2008: p 5.

(48) Yang, L.; Fan, C. J.; Wen, H. O.; Luo, M. K.; Sun, H.; Jia, C. An improved gas−liquid−solid coupling model with plastic failure for hydraulic flushing in gassy coal seam and application in borehole arrangement. *Phys. Fluids* **2023**, *35*, 036603.

(49) Wang, Z. F.; Fan, Y. C.; Li, S. S. Application of Borehole Hydraulic Flushing Technology to Soft and Outburst Seam with Low Permeability. *Coal Science and Technology* **2012**, *40* (02), 52−55.

(50) Wei, J. P.; Liu, Y. Z.; Wang, D. K.; Wen, Z. H.; Li, X. N. Numerical Simulation on Effective Influence Radius of Hydraulic Flushing Borehole. *Safety in Coal Mines* **2012**, *43* (11), 9−12.

(51) Wang, L. G.; Xu, Y. P. Study of the law of gradual change of the influence of hydraulic punching under a rational coal output. *Arabian Journal of Geosciences* **2019**, *12*, 427.

(52) Xu, D. D.; Tao, Y. Q.; Zhou, Z. T.; Hou, C. Study of the Law of Hydraulically Punched Boreholes on Effective Gas Extraction Radius under Different Coal Outputs. *Shock and Vibration* **2020**, *2020*, 8858091.

(53) Zhang, J. B.; Li, D. Q. Research on Optimization of Large Flow Hydraulic Punching Process in Zhao zhuang Mine. *Geofluids* **2022**, *2022*, 7535215.

(54) Wang, W.; Wang, G.; Zhao, W.; Wang, L.; Feng, Z.; Cui, R.; Du, F. Numerical assessment of the pressure relief effect of the hydraulic punching cavitation technique in a soft coal seam. *Geomechanics and Geophysics for Geo-Energy and Geo-Resources* **2022**, *8* (1), 1−18.

(55) Gu, B. F.; Wu, Y. L. Research and application of hydraulic punching pressure relief antireflection mechanism in deep ″three-soft″ outburst coal seam. *Shock and Vibration.* **2021**, *2021*, 7241538.

(56) Xu, Y.; Wang, L.; Bhattacharyya, S.; Peng, X.; Chen, X. Improving safety by further increasing the permeability of coal seams using air cannons after hydraulic punching. *Arabian journal of geosciences* **2021**, *14* (20), 14.

(57) Huang, Z. W.; Zhang, S. K.; Yang, R. Y.; Wu, X. G.; Li, R.; Zhang, H. Y.; Hung, P. P. A review of liquid nitrogen fracturing technology. *Fuel* **2020**, *266*, 117040.

(58) Allen, J. C.; Bauer, C. L. Method of increasing the permeability of a subterranean hydrocarbon bearing formation. US 36387274, 1968-09-27.

(59) McDaniel, B. W.; Grundmann, S. R.; Kendrick, W. D.; Wilson, D. R.; Jordan, S. W. Field applications of cryogenic nitrogen as a hydraulic fracturing fluid. *Journal of Petroleum Technology* **1998**, *50* (3), 38−39.

(60) Tian, M. M.; Zhang, Lei; Xue, J. H.; Zhang, C.; Lu, S.; Chen, S. Study and prospection of liquid nitrogen fracturing coal technology. *Coal Science and Technology* **2022**, *50* (07), 191−198.

(61) Cong, Y. Z.; Zhai, C.; Sun, Y.; Xu, J. Z.; Tang, W.; Zheng, Y. F. Visualized study on the mechanism of temperature effect on coal during liquid nitrogen cold shock. *Applied Thermal Engineering* **2021**, *194* (6), 116988.

(62) Akhondzadeh, H.; Keshavarz, A.; Al-Yaseri, A. Z.; Ali, M.; Awan, F. U. R.; Wang, X.; Yang, Y.; Iglauer, S.; Lebedev, M. Pore-scale analysis of coal cleat network evolution through liquid nitrogen treatment: a micro-computed tomography investigation. *International Journal of Coal Geology* **2020**, *219*, 103370.

(63) Nikolenko, P. V.; Epshtein, S. A.; Shkuratnik, V. L.; Anufrenkova, P. S. Experimental study of coal fracture dynamics under the influence of cyclic freezing−thawing using shear elastic waves. *International Journal of Coal Science & Technology* **2021**, 1−13.

(64) Zhang, C. H.; Xu, Ga; Yu, Y. J.; Wang, X. Z.; Wang, L. G. Study on permeability-enhancing mathematical model of coal fracturing with borehole water injection and liquid nitrogen injection. *Coal Science and Technology* **2019**, *47* (01), 139−144.

(65) Zhang, C. H.; Liu, P. S.; Wang, X. Z.; Guo, X. K.; Wang, L. G. Contrast test study on fracturing anthracite and coking coal by liquid nitrogen cooling. *Coal Science and Technology* **2017**, *45* (06), 30-34+ 49.

(66) Zhang, C. H.; Zhang, H. X.; Yu, Y. J.; Li, H. W.; Wang, L. G. Effects of saturation and re-submersion on coal fracturing subjected to liquid nitrogen shock. *Journal of China Coal Society* **2016**, *41* (S2), 400−406.

(67) Zhang, C. H.; Guo, X. K.; Li, H. W.; Zhao, N.; Wang, L. G. Study on influence of liquid nitrogen infiltration to saturated water coal fracture expanded. *Coal Science and Technology* **2016**, *44* (06), 99−105.

(68) Hou, P.; Su, S. J.; Gao, F.; Liang, X.; Wang, S. C.; Gao, Y. N.; Cai, C. Z. Influence of liquid nitrogen cooling state on mechanical properties and fracture characteristics of coal. *Rock Mechanics and Rock Engineering* **2022**, *55* (7), 3817−3836.

(69) Su, S. J.; Hou, P.; Gao, F.; Gao, Y. N.; Cai, C. Z.; Zhang, Z. Z.; Liang, X. A fractal perspective on structural damage and fracture characteristics of coal subjected to liquid nitrogen cooling at laboratory-scale. *FRACTALS (fractals)* **2022**, *30*, 30.

(70) Liu, S. M.; Sun, H. T.; Zhang, D. M.; Yang, K.; Wang, D. K.; Li, X. L.; Long, K.; Li, Y. N. Nuclear magnetic resonance study on the influence of liquid nitrogen cold soaking on the pore structure of different coals. *Phys. Fluids* **2023**, *35* (1), 012009.

(71) Zhai, C.; Sun, Y. Experimental study on evolution of pore structure in coal after cyclic cryogenic fracturing. *Coal Science and Technology* **2017**, *45* (06), 24−29.

(72) Zhai, C.; Sun, Y.; Wu, J. G. New Progress of Liquid Nitrogen Fracture Technique in Low-permeability Coal Seams. *Bulletin of National Natural Science Foundation of China* **2021**, *35* (06), 904−910.

(73) Longinos, S. N.; Serik, A.; Zhang, D. C.; Wang, L.; Hazlett, R. Experimental Evaluation of Liquid Nitrogen Fracturing on the Coal Rocks in Karaganda Basin, Kazakhstan. *Arabian Journal for Science and Engineering* **2023**, DOI: 10.1007/s13369-023-07857-y.

(74) Jiang, Z. B.; Xiping; Quan, X. P.; Tian, S. X.; Liu, H.; Guo, Y. L.; Fu, X. X.; Yang, X. F. Permeability-Enhancing Technology through Liquid CO_2 Fracturing and Its Application. *Sustainability* **2022**, *14*, 10438.

(75) Wang, H. D.; Cheng, Z. H.; Zou, Q. L.; Li, Z. H.; Sun, F. L.; Yang, H. W.; Lei, Y. Elimination of coal and gas outburst risk of an outburst-

prone coal seam using controllable liquid CO_2 phase transition fracturing. *Fuel* **2021**, *284*, 119091.

(76) Saghafi, A. Potential for ECBM and CO_2 storage in mixed gas Australian coals. *International Journal of Coal Geology* **2010**, *82* (3−4), 240−251.

(77) Liao, Z. W.; Liu, X. F.; Song, D. Z.; He, X. Q.; Nie, B. S.; Yang, T.; Wang, L. K. Micro-structural damage to coal induced by liquid CO_2 phase change fracturing. *Natural Resources Research* **2021**, *30*, 1613.

(78) Wen, H.; Wei, G. M.; Ma, L.; Li, Z. B.; Lei, C. K.; Hao, J. C. Damage characteristics of coal microstructure with liquid CO_2 freezing-thawing. *Fuel* **2019**, *249*, 169−177.

(79) Liu, H.; Liu, G. F.; Zhang, Z.; Li, B. L.; Si, N.; Guan, W. B.; Lin, J. Effects of Liquid CO_2 Phase Transition Fracturing on Mesopores and Micropores in Coal: Energy. *Fuels* **2022**, *36*, 10016−10025.

(80) Liu, X. F.; Wang, Z. P.; Song, D. Z.; He, X. Q.; Yang, T. Variations in surface fractal characteristics of coal subjected to liquid CO_2 phase change fracturing. *International Journal of Energy Research* **2020**, *44* (4), 8740−8753.

(81) Xia, B. W.; Liu, X. F.; Song, D. Z.; He, X. Q.; Yang, T.; Wang, L. K. Evaluation of liquid CO_2 phase change fracturing effect on coal using fractal theory. *Fuel* **2021**, *287*, 119569.

(82) Yu, R.; Wang, X. F.; Wang, Z. F.; Wang, L.; Zhang, X. Q.; Liu, W. G.; Zhang, Q. Study on the Mechanism of Liquid Carbon Dioxide Fracturing and Permeability Enhancement Technology in Low Permeability Thick Coal Seam. *Geofluids* **2022**, *2022*, 4688347.

(83) Dong, Q. X.; Wang, Z. F.; Han, Y. B.; Sun, X. M. Research on TNT equivalent of liquid CO_2 phase-transition fracturing. *China Safety Science Journal* **2014**, *24* (11), 84−88.

(84) Wang, Z. F.; Sun, X. M.; Lu, Tk; Han, Y. B. Experiment research on strengthening gas drainage effect with fracturing technique by liquid CO_2 phase transition. *Journal of Henan Polytechnic University (Natural Science)* **2015**, *34* (01), 1−5.

(85) Wang, Z. F.; Li, H. J.; Chen, X. E.; Zhao, L.; Zhou, D. C. Study on hole layout of liquid CO_2 phase-transforming fracture technology for permeability improvement of coal seam. *Journal of Safety Science and Technology* **2015**, *11* (09), 11−16.

(86) Li, H. J.; Wang, Z. F.; Chen, Xien; Zhao, L.; Zhou, D. C. Optimization of borehole layout parameters based on fracturing technology of liquid CO_2 phase. *Coal Geology & Exploration* **2017**, *45* (04), 31-37+ 43.

(87) Zhang, D. M.; Bai, X.; Yin, G. Z.; Lin, S. J.; Rao, Z.; He, Q. B. Mechanisms of breaking and fracture expansion of liquid CO_2 phase change jet fracturing in low-permeability coal seam. *Journal of China Coal Society* **2018**, *43* (11), 3154−3168.

(88) Jia, J. Z.; Wang, D. M.; Li, B.; Tian, X. Y. Study of the influencing factors of the liquid CO_2 phase change fracturing effect in coal seams. *PLoS One* **2021**, *16* (7), No. e0254996.

(89) Hu, X. Y.; Zhang, R. X.; Zhang, B. L.; Zhang, X. H.; Zhang, L. L.; Yang, Y. D.; Yan, F. Z. A Study on the Factors Influencing Coal Fracturing Range Caused by Liquid Carbon Dioxide Phase Transition. *Geofluids* **2022**, *2022*, 4754764.

(90) Wu, X. H.; Zhu, T.; Liu, Y. F.; Zhang, G. Y.; Zhang, G. H.; Wang, F. N. Mechanism of Coal Seam Permeability Enhancement and Gas Outburst Prevention under Hydraulic Fracturing Technology. *Geofluids* **2022**, *2022*, 9 Article ID 7151851.