

Study on the Mechanism of Coal Fracturing by Liquid Nitrogen

Haifeng Wang^{1, *}

¹Henan Polytechnic University, School of Resource & Environment, Jiaozuo, China

*Corresponding Author

ABSTRACT

As a fracturing medium with excellent properties, liquid nitrogen has multiple fracturing effects on coal, and its potential application in coalbed methane mining has become a hot spot in current research. In this paper, the key scientific problems of fracturing and penetration enhancement by liquid nitrogen in low-permeability coals are discussed in depth, and the pore fracturing process and its fracturing mechanism of low-temperature fracturing coal are analyzed. It is found that the ultra-low-temperature fluid fracturing process has the effect of high-energy fluid fracturing to break the rock, and also has the coupled fracturing effect of low-temperature fracturing and phase-change fracturing to increase the energy-driven replacement. It aims to provide theoretical basis and technical support for the efficient and environmentally friendly exploitation of low-permeability oil and gas fields.

KEYWORDS

Liquid nitrogen fracturing; Low-permeability reservoirs; Fracturing mechanism.

1. INTRODUCTION

Coal is an important part of China's energy, but also an important driving force for national economic development [1]. Energy security supply is the basis of high-quality development, "lack of oil, less gas, relatively rich in coal" energy structure of China's "coal as the main body" of the basic national conditions, which also determines the dominant position of coal in China's energy consumption structure for a long time unchanged [2]. China is rich in coal resources, and the large amount of coalbed methane (CBM) mining has made great contributions to China's economic development. According to recent statistics, China's CBM resources with a burial depth of 1,000 m to 2,000 m are as high as $22.54 \times 10^{12} \text{ m}^3$, accounting for 61.23% of the CBM resources above 2,000 m [3]. However, the permeability of coal beds decreases dramatically due to the large tectonic stress, forming the typical characteristics of "three lows and one high", such as low permeability, high gas content, low reservoir pressure and low gas saturation, which brings great difficulties to the exploitation of CBM [4]. According to statistics, in 2023, China's CBM extraction volume has increased to 13.94 billion m^3 , and compared with the 10 trillion m^3 of resource reserves at a depth of 2,000 m, the development level of CBM extraction is relatively low [5]. Microfissures of different scales in coal are the space for gas storage and the channel for communication between diffusion and seepage, and their degree of development determines the permeability of coal reservoirs. Therefore, the formation of a moderate-scale microfracture network and maintaining its connectivity is the key to the efficient transportation of CBM.

Liquid nitrogen (LN_2), as an efficient refrigeration and permeability enhancement medium, has the advantages of simple preparation, wide source of raw materials, easy to use and environmentally friendly and non-polluting, etc. LN_2 temperature at atmospheric pressure can reach $-196 \text{ }^\circ\text{C}$, and the

vaporization and expansion of pure nitrogen at 21 °C has an expansion rate of 696 times, and it can produce huge stresses in a limited space [6-8]. At present, the low-temperature fluid fracturing technology such as liquid nitrogen has been widely concerned by domestic and foreign researchers and has been tried in the engineering application of rock fracturing. Compared with hydraulic fracturing and acidization to increase production, the LN₂ fracturing technology not only solves the problems of wasting water resources and polluting groundwater, but also successfully avoids the water-locking and water-sensitive effects of the reservoirs, which is a feasible method to improve the permeability of coal reservoirs. This paper systematically describes the mechanism of LN₂ fracturing process in low-permeability reservoirs, and provides references and ideas for the engineering of LN₂ fracturing technology in low-permeability oil reservoirs.

2. PROCESS AND MECHANISM OF FRACTURING LOW-PERMEABILITY COAL BEDS WITH LN₂

By using high pressure and large displacement, LN₂ is injected into the coal reservoir, which results in a strong thermal impact on the coal. The fracturing process of the coal seam under low temperature conditions can be divided into three stages: firstly, the high-pressure liquid nitrogen cycle freezing-thawing (LNCFT) the coal in a fluid form, similar to the hydraulic fracturing process, leading to the generation and expansion of the main fractures in the coal seam; secondly, the differential deformation and fracturing stage resulting from the thermal exchange between low temperature LN₂ and coal is a typical low temperature freeze-thaw process, contributing to the formation of micro-fractures network in the coal; finally, the gas-phase fracturing and pressure enhancing process caused by the phase transition expansion of LN₂ drives the displacement of CH₄ in the coal seam, similar to nitrogen plugged wells, while simultaneously achieving the synergistic effect of reservoir pressure enhancement and permeability improvement through displacement. The interaction and influence of these three stages determine the effectiveness of the low-permeability reservoir transformation.

2.1. Rock breaking processes with high pressure fluids

The high-pressure fluid fracturing stage involves LN₂ entering coal fractures in fluid form (mainly liquid), fracturing the coal body like high-pressure water when the fracturing pressure exceeds the rock mechanical strength. The premise and key to this process is that LN₂ under high pressure can exist in a fluid state in the coal wall. In 1756, Leidenfrost discovered that water droplets can float and roll on a sufficiently hot solid surface, a phenomenon known as the Leidenfrost phenomenon. The condition for its occurrence is that when a low-temperature liquid comes into contact with a high-temperature surface, the liquid near the surface rapidly vaporizes and produces an insulating layer of vapor, preventing the remaining liquid from coming into contact with the hot surface and undergoing rapid boiling [9]. According to the temperature difference between the liquid and the surface, boiling heat transfer can be divided into two categories: the phenomenon of stable vapor film formation on a hot surface with a large temperature difference is called film boiling; the phenomenon of bubble generation on a hot surface with a small temperature difference is called nucleate boiling, in which the rate of bubble generation is lower than the rate of bubble detachment from the heated surface; the phenomenon of unstable vapor film formation on the heated surface when the rate of bubble generation exceeds the rate of bubble detachment from the heated surface is called transition boiling.

The LN₂ itself has a very low temperature (-196 °C). When the high-pressure LN₂ enters the coal seam (assuming that the coal seam is buried at a depth of 500-600 m, the temperature is about 30 °C, and the deep temperature is higher), it can produce a temperature difference of more than 226 °C, which exceeds the Leidenfrost point of 193 °C. The huge temperature difference causes a large amount of gasification of LN₂ on the surface of the coal-rock fracture wall, that is, the LN₂ and the coal wall are covered by a steam layer (mainly nitrogen). The heat conduction between the LN₂ and the coal wall is completed by conduction and radiation through the steam layer. It is a typical film

boiling phenomenon; then, with the heat exchange between LN₂ and coal wall, the temperature of the LN₂ infiltration area suddenly decreases, and the phenomenon of nucleate boiling and natural convection boiling occurs at this time. In general, the initial temperature conduction of LN₂ into coal is not as efficient as people originally thought, which is subject to the heat conduction process and efficiency between LN₂ and coal wall. Wang et al. [10] studied the change of LN₂ phase state when LN₂ was introduced into a normal temperature pipeline. It was found that in the initial time, because the wall temperature was much higher than the boiling point of LN₂, the front end of the pipeline was mainly characterized by film boiling. With the passage of time, the wall pipeline was gradually cooled, and the area of film boiling gradually increased. In the later period, the front end of the pipeline was characterized by film boiling and the rear part was characterized by the coexistence of nucleate boiling. The nucleate boiling area gradually increased after cooling the LN₂ pipeline; Darr et al. [11] calculated the evolution process of temperature and thermal convection density after LN₂ was continuously introduced into the pipeline. It was found that the temperature decreased slowly in the film boiling state, and the temperature decreased sharply when it entered the nucleate boiling state, which also implied that the initial stage of LNCFT showed more hydraulic fracturing behavior, while the later stage showed the heat exchange effect of temperature. Cha et al. [12-13] found that when sandstone was placed in LN₂ for cold immersion experiment, it took up to 7 min for the sandstone to decrease from room temperature to LN₂ temperature, and the temperature reduction rate was only 0.5 °C/s, which would reduce the reservoir temperature more slowly. Coal is a reservoir with slower heat conduction than sandstone, so the fluid state can be maintained for a long time after LN₂ is injected into the coal seam [14]. Wang et al. [15] and Li et al. [16] found that it takes a long time (even more than 40 min) for LN₂ to reach the equilibrium temperature, which provides sufficient time guarantee for LN₂ to maintain liquid and high-pressure fluid fracturing, which is also the key to fluid fracturing.

Different from the fracturing process of conventional fracturing, LNCFT is a low temperature fracturing process, which makes LNCFT unique. Hong et al. [17] studied the process of LN₂ and water fracturing visual material PMMA (Polymethyl Methacrylate), and found that LNCFT can greatly reduce the initiation pressure of the reservoir (decreased by 47.1 % -71.7 %), forming a complex fracture network characterized by ' Thermal stress fracture + Main fracture '. Compared with hydraulic fracturing, lower cycle times and injection pressure can achieve better fracture effect. Some scholars also pointed out that even a simple LN₂ cold shock and cooling process can also generate a complex fracture system [18]. In this process, the fractures produced by low temperature fluid fracturing coal and its relationship with natural fractures determine the scale and complexity of the first stage of fracture formation. In-situ stress, the scale of primary fractures, the angle between new fractures and natural fractures and their action process are the main controlling factors [19].

2.2. Low temperature LN₂ freeze-thaw fracturing process

After high-pressure LN₂ is pressed into the coal seam, in addition to fracturing the coal body, it is also accompanied by a wide range of later effects, including the heat exchange process between the low-temperature fluid and the coal, the low-temperature freeze-thaw reaction, the frost heave reaction caused by the water-ice phase transition, and the gas expansion deformation fracturing reaction caused by the LN₂ gasification. These processes often interact with each other to form a more complex deformation and fracturing process. In fact, it is the temperature exchange process between LN₂ and coal (the thermal shock process of LN₂ on coal). According to the low temperature-phase transition process between LN₂ and reservoir, it can also be refined into three processes: the initial temperature exchange process. The mid-term freeze-thaw fracturing process and the later phase change process, in which the LNCFT process of the first two processes is dominant.

2.2.1. Temperature exchange process

The initial temperature exchange process refers to the temperature exchange and deformation between LN₂ and coal wall after entering the coal seam, including temperature conduction mechanism and coal shrinkage-differential deformation. The temperature exchange method in this process is heat conduction. Heat conduction is a heat transfer phenomenon when there is no macroscopic movement in the medium. When LN₂ contacts the surface of coal, ultra-low temperature LN₂ will quickly absorb the heat on the surface of coal and reduce the surface temperature [20]. From the perspective of molecular vibration, the heat conduction between LN₂ and coal is realized by the vibration of the basic structural unit (BSU) of crystal-like coal, and natural convection will occur in the fluid due to the density difference caused by the temperature gradient. It promotes the transfer of high-temperature fluid to low-temperature fluid and continuously radiates electromagnetic waves. Heat conduction, convection and radiation occur simultaneously during the fracturing process of low-temperature fluid, which jointly promotes temperature exchange during the fracturing process and provides a basis for infrared detection technology to detect low-temperature conduction processes. Chu et al. [21] used infrared thermal imaging technology to study the temperature distribution characteristics of coal samples after LNCFT, and revealed the effect of temperature on the mechanical properties of coal during LNCFT. Ma [22] detected the change of radiation temperature in the process of coal fracture by infrared, and found that the temperature change had a good linear positive correlation with the porosity and stress change of coal body.

With the continuous exchange of LN₂ and coal energy, the surface temperature of coal gradually decreases and the temperature difference gradient between LN₂ and coal is reduced. A cooling zone is formed on the surface of the rock mass until the heat flux exceeds the Leidenfrost temperature. Therefore, the LN₂ in the coal fracture changes from the initial film boiling state to the transition boiling and nucleate boiling state. This process makes the temperature resistance of the steam cushion disappear, and the LN₂ changes from the fluid to the vapor-liquid mixed phase, resulting in a rapid increase in the heat convection on the surface of the coal fracture wall, which further accelerates the temperature exchange rate between the LN₂ and the surface of the rock mass, resulting in a rapid decrease in the temperature of the coal. Macroscopically, the low temperature impact process will degrade the mechanical properties of rock mass, greatly reduce the compressive strength, tensile strength and Young's modulus of rock, thus reducing the fracture pressure of rock [23]. Taking LN₂ fracturing coal as an example, the uniaxial compressive strength of coal samples after LN₂ treatment is reduced by 16.18% -33.74%, and the axial peak stress is reduced by 13% -21%, showing obvious deterioration [24]. Microscopically, the low temperature effect changes the stress field inside the rock, so that the fractures no longer extend along the direction of the original maximum principal stress, but extend along the areas with weak mechanical properties and more complex mineral composition in the coal components, thus forming a dense fracture network [25]. The main reasons are from two aspects: (1) The sharp decrease of temperature leads to rapid shrinkage deformation between different types of coal components and organic-inorganic structures. Due to the difference of shrinkage coefficients of different coals, deformation mismatch occurs and leads to the formation of shear fractures. (2) In the water-bearing reservoir, the rapid cooling process will cause the pore water in the reservoir to freeze into ice and produce frost heave stress (up to 207 MPa), thus promoting fracture bifurcation. From the current research results, how the new fractures communicate with the original fractures and extend, cut off, cross, and complicate the process is still the focus of future research, and its interaction process mechanism under low temperature conditions has not been revealed. In view of the different resistance effects between different rocks, due to the influence of rock composition, structure, porosity, original temperature and other factors, the cooling efficiency and fracturing effect of tight rocks such as coal, shale, sandstone and granite are also different. With the exchange of fluid and coal temperature, the low temperature fluid and rock surface will eventually reach a state of thermal equilibrium. At this time, the temperature gradient and fracturing effect are no longer obvious, the rate of heat conduction gradually slows down, and the energy exchange maintains balance.

2.2.2. The process of intermediate freezing-thawing fracturing

The water-ice phase transition is considered to be the predominant factor causing fracturing in the low-temperature freezing and thawing process of LN₂. During this process, pore water freezes, resulting in the formation of ice lenses through hydrogen bonding between four water molecules. These ice lenses induce approximately 9% volume expansion stress. Consequently, fractures in coal can also expand due to this phenomenon [26]. Numerous experiments have demonstrated that saturated coal samples exhibit significantly higher susceptibility to low temperature fracturing compared to dry samples [27]. Moreover, an increase in water content leads to longer and denser fractures within coal, with saturated coal samples exhibiting a much greater increase in new fractures compared to dry samples (10-20 times) [28].

At present, most of the conclusions believe that the low temperature of LN₂ will cause the phase change of water in the pores of coal and rock and cause volume expansion (volume increase of about 9%), which will produce huge frost heave force (more than 207 MPa) at the tip of the pore fracture and lead to fracture expansion [29]. Under the influence of siphon, the unfrozen free water will migrate to the frozen area, and the extrusion stress generated by frozen ice and free water will also increase the damage of coal. However, this process needs to meet the harsh conditions of space closure, high saturation and long freezing time at the same time, which is easy to achieve in the laboratory. However, it is not easy to maintain sufficient freezing and thawing time or maintain space closure under in-situ conditions. More importantly, saturated water can increase frost heaving force but hinder LN₂ migration channel, thus affecting the subsequent temperature conduction process and fracturing effect. Recently, the study on the fracture mechanism of low-temperature rock mass in cold regions has found that water will also form a Segregation ice in the fractures of low-temperature rock mass. Under the action of the segregation potential, the water in the unfrozen area will migrate to the edge of the ice lens and lead to the growth of the ice lens. When the ice lens continues to grow and squeeze the fracture wall, it can also lead to rock fracture [30-31]. This discovery breaks the limitation that the water-ice phase transition requires sealing space and saturated water, so that the micro-fracture rupture position is not only limited to the fracture tip, but also may appear in the formation area of any ice lens (especially the structural weak plane position in coal). Is this the reason for the complex fracture network under saturated water conditions? Further research is needed.

2.3. Liquid-gas phase change fracturing process

The temperature of LN₂ can be as low as -196 °C. After the LN₂ is injected into the coal seam under high pressure, the temperature decreases and then recovers. The LN₂ will produce a strong vaporization phase change. The 1 m³ LN₂ can expand to 696 m³ nitrogen (21 °C), which can absorb 160.8 kJ of heat and produce a strong expansion force while sharply reducing the reservoir temperature. Under in-situ conditions, it is difficult to expand fractures by relying solely on LN₂ phase change. However, considering the deteriorating mechanical properties of coal and rock during low-temperature freeze-thaw process, this possibility cannot be denied. In fact, the vaporization energy increase and adsorption expansion deformation in the process of LNCFT are much stronger than those of conventional hydraulic fracturing, and the resulting subsidiary effects should be considered: first, the gas expansion caused by the vaporization of ultra-low temperature fluid and its deterioration of coal strength; the second is the high pressure fracturing and heat conduction effect caused by the phase transition process. These effects will have different degrees of influence on the integrity of coal matrix and pore structure, such as gas expansion fractures [32]. The experiment found that after injecting N₂ or CO₂ into the coal body, it has the functions of fracturing and increasing permeability, pressurization and increasing energy, and diffusion displacement [33]. The increase of permeability and production after N₂ injection-soak can also prove the influence of phase change process on coal structure [34]. It is a recognized fact that the expansion deformation of coal will occur after gas adsorption. The expansion deformation of coal is positively correlated with adsorption capacity, gas pressure and carbon content, and negatively correlated with water content [35]. Although the

expansion amount of N₂ and CH₄ mixed adsorption is less than that of pure CH₄ adsorption, and several times lower than that of CO₂ adsorption, considering the high liquid-gas ratio and low temperature environment of LN₂, the strong vaporization pressurization and adsorption expansion deformation in the process of LNCFT are much stronger than that of normal pressure adsorption expansion deformation. How to superimpose LN₂ high pressure fracturing, thermal stress and frost heaving force is also a problem worthy of study.

In fact, the process of LN₂ injection into coal will experience the change process of liquid, gas and supercritical state. The energy conduction interaction between multiphase fluid and coal involves the evolution coupling of stress field, temperature field and fracture field. Methods such as CO₂ phase change blasting, supercritical CO₂ fracturing, or low-temperature LNCFT all contain strong liquid-gas phase change processes. In this process, changes in pore morphology and structural integrity in coal have been widely concerned [36], but the change of gas state to supercritical state and its subsidiary effects need to be further studied.

Cryogenic LN₂ fracturing technology is a method of fracturing rock to improve permeability by utilizing fluids in a low-temperature state. In essence, the low-temperature property of LN₂ is utilized to cause the transformation of gas-liquid and ice-water phases in the coal-rock reservoir, and the thermal and expansion stresses work together to induce the main fracture initiation, the main fracture expansion, and the growth of thermal stress cracks [104]. The whole fracturing process can be divided into two stages: freezing and melting. In the fracturing freezing stage, the low-temperature effect induces rock surface contraction, deformation between mineral particles, freezing of pore fluids, and changes in the mechanical properties of coal. The coal body changes from tensile stress to compressive stress as the coal reservoir undergoes the cold shock process. This freezing and thawing effect will further lead to an increase in pressure within the pores, promoting the secondary development of cracks and the formation of a dense fracture network.

3. CONCLUSION

In this paper, the mechanism of fracturing low-permeability reservoirs with LN₂ is discussed in depth, and the following conclusions are drawn: fracturing reservoirs with low-temperature LN₂ fracturing can be divided into three parts: high-pressure fluid rock-breaking, low-temperature freezing and thawing fracturing, and phase change fracturing with LN₂. Among them, the process of fracturing coal by high-energy fluid is similar to that of hydraulic fracturing, the process of low-temperature-phase-change coupled fracturing is the key stage for the formation of microfracture network, the mismatch deformation of different coal-rock components under the effect of temperature difference is the key to fracture the coal body by ultra-low-temperature fluid, and the phase-change fracturing is the decisive factor to determine the size of the fissure, and the three of them interact with each other and affect each other, and their combined effect determines the fracturing effect of the low-permeability reservoirs.

REFERENCES

- [1] Liu C, Zhu J, Che C, et al. Methodologies and results of the latest assessment of coalbed methane resources in China [J]. *Natural Gas Industry*. 2009, 29(11): 130-132.
- [2] Zhang Q, Feng S, Yang X. Basic reservoir characteristics and development strategy of coalbed methane resource in China [J]. *Journal of China Coal Society*. 2001, 26(3): 230-235.
- [3] Mu F, Zhong W, Zhao X, et al. Strategies for the development of CBM gas industry in China[J]. *Natural Gas Industry*. 2015, 35(6): 110-116.
- [4] Barati R, Liang J T. A review of fracturing fluid systems used for hydraulic fracturing of oil and gas wells[J]. *Journal of Applied Polymer Science*. 2014, 131(16).
- [5] Xu F, Hou W, Xiong X, et al. The status and development strategy of coalbed methane industry in China[J]. *Petroleum Exploration and Development*. 2023, 50(4): 669-682.

- [6] Qin L, Zhai C, Liu S, et al. Mechanical behavior and fracture spatial propagation of coal injected with liquid nitrogen under triaxial stress applied for coalbed methane recovery[J]. *Engineering Geology*, 2017,233:1-10.
- [7] Qin L, Zhai C, Liu S, et al. Changes in the petrophysical properties of coal subjected to liquid nitrogen freeze-thaw – A nuclear magnetic resonance investigation[J]. *Fuel*, 2017,194:102-114.
- [8] Huang Q, Liu S, Wang G, et al. Coalbed methane reservoir stimulation using guar-based fracturing fluid: a review. *J Nat Gas Sci Eng* 66: 107–125[J]. 2019.
- [9] Leidenfrost J G. On the fixation of water in diverse fire[J]. *International Journal of Heat and Mass Transfer*. 1966, 9(11): 1153-1166.
- [10] Wang J, Li Y, Wang L, et al. Thermal prediction of transient two-phase flow in cryogenic transportation based on drift-flux model[J]. *International Journal of Heat and Mass Transfer*. 2021, 177: 121512.
- [11] Darr S R, Hu H, Glikin N G, et al. An experimental study on terrestrial cryogenic transfer line chilldown I. Effect of mass flux, equilibrium quality, and inlet subcooling[J]. *International Journal of Heat and Mass Transfer*. 2016, 103: 1225-1242.
- [12] Cha M, Yin X, Kneafsey T, et al. Cryogenic fracturing for reservoir stimulation – Laboratory studies[J]. *Journal of Petroleum Science and Engineering*. 2014, 124: 436-450.
- [13] Li R, Huang Z, Wu X, et al. Cryogenic quenching of rock using liquid nitrogen as a coolant: Investigation of surface effects[J]. *International Journal of Heat and Mass Transfer*. 2018, 119: 446-459.
- [14] Xu S. Study on the distribution law and control mode of geothermal field in Huainan-Huaibei Coalfield[D]. Anhui University of Science and Technology. 2014.
- [15] Wang C, Zhang X, Lu F. Study on coal cracking under liquid nitrogen soaking based on nuclear magnetic resonance and stress analysis[J]. *China Safety Science Journal*. 2019, 29(11): 156-163.
- [16] Li B, Ren Y, Zhang L, et al. Study on influence mechanism of liquid nitrogen to permeability improved function of water bearing coal and rock mass[J]. *Coal Science and Technology*. 2018, 46(12): 145-150.
- [17] Hong C, Yang R, Huang Z, et al. Visualization of fracture initiation and morphology by cyclic liquid nitrogen fracturing [J]. *Petroleum Science Bulletin*. 2023, 8(1): 87-101.
- [18] Jin X, Gao J. Research on conversion of brittleness to ductility of coal with liquid nitrogen cryogenic[J]. *China Coal*. 2018, 44(12): 99-105.
- [19] Guo X, Zhong J, Xu X, et al. Development characteristics and genetic mechanism of the untectonic fracture[J]. *Journal of China University of Petroleum (Edition of Natural Science)*. 2004, 28(2): 6-11.
- [20] Chen J, Fang H. Heat under the microscope[J]. *Physics*. 2014, 43(8): 552-553.
- [21] Chu Y, Zhang D, Yang H, et al. Study on evolution law of mechanical properties of coal samples subjected to freezing and freeze-thaw cycles of liquid nitrogen[J]. *Coal Science and Technology*. 2023, 51(5): 82-92.
- [22] Ma L, Li Q, Cao X, et al. Variation characteristics of internal infrared radiation temperature of coal-rock mass in compression process[J]. *Journal of China University of Mining & Technology*. 2013, 42(03): 331-336.
- [23] Akhondzadeh H, Keshavarz A, Al-Yaseri A Z, et al. Pore-scale analysis of coal cleat network evolution through liquid nitrogen treatment; a micro-computed tomography investigation[J]. *International journal of coal geology*. 2020, 219: 103370.
- [24] Huang Z, Zhang S, Yang R, et al. A review of liquid nitrogen fracturing technology[J]. *Fuel*. 2020, 266: 117040.
- [25] Huang Z, Wen H, Wu X, et al. Experimental study on cracking of high temperature granite using liquid nitrogen[J]. *Journal of China University of Petroleum (Edition of Natural Science)*. 2019, 43(2): 68-76.
- [26] Cai C, Li G, Huang Z, et al. Experiment of coal damage due to super-cooling with liquid nitrogen[J]. *Journal of Natural Gas Science and Engineering*. 2015, 22: 42-48.
- [27] Wang L, Yao B, Cha M, et al. Waterless fracturing technologies for unconventional reservoirs-opportunities for liquid nitrogen[J]. *Journal of natural gas science and engineering*. 2016, 35(PA): 160-174.
- [28] Li Y, Wang H, Song D, et al. The evolution process of fractures and their modification effects on the liquid–solid interface during liquid nitrogen cyclic freeze–thaw of coal and shale[J]. *Fuel*. 2024, 362: 130877.
- [29] Sandström T, Fridh K, Emborg M, et al. The influence of temperature on water absorption in concrete during freezing[J]. *Nordic Concrete Research*. 2012, 45(1): 45-58.
- [30] Hallet B. Why do freezing rocks break?[J]. *Science*. 2006, 314(5802): 1092-1093.
- [31] Liu Q, Huang S, Kang Y, et al. Advance and review on freezing-thawing damage of fractured rock[J]. *Chinese Journal of Rock Mechanics and Engineering*. 2015(3): 452-471.
- [32] Pan Z, Connell L. A theoretical model for gas adsorption-induced coal swelling[J]. *International Journal of Coal Geology*. 2007, 69(4): 243-252.
- [33] Wang Z, Fu X, Deng Z, et al. Investigation of Adsorption–Desorption, Induced Strains and Permeability Evolution During N₂–ECBM Recovery[J]. *Natural Resources Research*. 2021, 30: 3717-3734.

- [34] Zhang D, Bai X, Yin G, et al. Research and application on technology of increased permeability by liquid CO₂ phase change directional jet fracturing in low-permeability coal seam[J]. Journal of China Coal Society. 2018, 43(07): 1938-1950.
- [35] Cao Y, Shi B, Zhou D, et al. Study and application of stimulation technology for low production CBM well through high pressure N₂Injection-soak[J]. Journal of China Coal Society. 2019, 44(08): 2556-2565.
- [36] Xu J. Study of Pore Evolution and Damage Mechanical Characteristics of Coals under the Effect of Liquid CO₂ Cyclic Shock Fracturing[D]. China University of Mining and Technology. 2020.