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Review

Mechanism and Model Analysis of Ultralow-Temperature Fluid Fracturing in Low-Permeability Reservoir: Insights from Liquid Nitrogen Fracturing

Haifeng Wang [1,2], Yunbo Li [1,2], Dangyu Song [1,2], Meng Lin [3,*], Xingxin Guo [1,2] and Xiaowei Shi [4]

[1] School of Resource & Environment, Henan Polytechnic University, Jiaozuo 454000, China
[2] State Key Laboratory Cultivation Base for Gas Geology and Gas Control, Henan Polytechnic University, Jiaozuo 454000, China
[3] Henan Gas Control Research Institute Co., Ltd., Zhengzhou 450000, China
[4] Henan Academy of Geology, Zhengzhou 450016, China
* Correspondence: aceslynn1314@foxmail.com

Abstract: Ultralow-temperature fluids (such as liquid nitrogen, liquid CO_2) are novel waterless fracturing technologies designed for dry, water-sensitive reservoirs. Due to their ultralow temperatures, high compression ratios, strong frost heaving forces, and low viscosities, they offer a solution for enhancing the fracturing and permeability of low-permeability reservoirs. In this study, we focus on the combined effects of high-pressure fluid rock breaking, low-temperature freeze-thaw fracturing, and liquid-gas phase transformation expansion on coal-rock in low-permeability reservoirs during liquid nitrogen fracturing (LNF). We systematically analyze the factors that limit the LNF effectiveness, and we discuss the pore fracture process induced by low-temperature fracturing in coal-rock and its impact on the permeability. Based on this analysis, we propose a model and flow for fracturing low-permeability reservoirs with low-temperature fluids. The analysis suggests that the Leidenfrost effect and phase change after ultralow-temperature fluids enter the coal support the theoretical feasibility of high-pressure fluid rock breaking. The thermal impact and temperature exchange rate between the fluid and coal determine the temperature difference gradient, which directly affects the mismatch deformation and fracture development scale of different coal-rock structures. The low-temperature phase change coupling fracturing of ultralow-temperature fluids is the key to the formation of reservoir fracture networks. The coal-rock components, natural fissures, temperature difference gradients, and number of cycles are the key factors in low-temperature fracturing. In contrast to those in conventional hydraulic fracturing, the propagation and interaction of fractures under low-temperature conditions involve multifield coupling and synergistic temperature, fluid flow, fracture development, and stress distribution processes. The key factors determining the feasibility of the large-scale application of ultralow-temperature fluid fracturing in the future are the reconstruction of fracture networks and the enhancement of the permeability response in low-permeability reservoirs. Based on these considerations, we propose a model and process for LNF in low-permeability reservoirs. The research findings presented herein provide theoretical insights and practical guidance for understanding waterless fracturing mechanisms in deep reservoirs.

Keywords: cryogenic fluid; liquid nitrogen fracturing mechanism; low-permeability reservoirs; gas transportation; fracturing mode

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1. Introduction

China has abundant coalbed methane (CBM) resources, with shallow CBM resources (within 2000 m) estimated at 36.8 trillion m^3 and deep resources (over 1500 m) accounting for one-third of the total CBM resources, ranking China third in the world and providing assurance for its national energy security [1,2]. In 2023, China's surface CBM production was only 11.77 billion m^3, accounting for 3.48% of that year's natural gas production, with an average single-well production rate of less than 800 m^3/d. The main reasons for this low production rate include low permeability, low gas saturation, and widespread structural coal in the coalbeds, with over 60% of coalbeds with permeabilities lower than 0.1 mD, resulting in the need for hydraulic fracturing in over 90% of the CBM wells to create fracture networks to enhance production. Effective permeability and production enhancement with suitable technologies remains a significant challenge in the industry [3,4]. Since the successful implementation of hydraulic fracturing in the Klepper well in Grant County, Kansas, the United States, in 1947, hydraulic fracturing has evolved over half a century to become the predominant reservoir reconstruction technology. Once the fracture pressure threshold of a reservoir is surpassed, high-pressure water injection triggers the activation and expansion of the natural fractures surrounding the wellbore, leading to the formation of an interconnected fracture network that enhances the reservoir's permeability [5–8]. However, the transformation of the coal seams via hydraulic fracturing is accompanied by a series of challenges. First, substantial water requirements restrict its applicability in arid regions. Second, the additives present in fracturing fluids (e.g., NaCl, bactericides, and wetting agents) can lead to water pollution. Finally, the presence of water-sensitive minerals in coal (e.g., montmorillonite and illite) can cause expansion and subsequent blockage within the fractures. These factors contribute to a reduced gas migration efficiency or even to the complete absence of gas production. Therefore, the development of novel fracturing techniques and methodologies is imperative.

To address the challenges posed by hydraulic fracturing, as early as the 1990s, scholars began proposing the substitution of conventional water-based fracturing fluids with high-pressure LN_2 injection into the coal seams. LN_2 is the primary fluid used for fracturing low-permeability reservoirs, and its preparation technology plays a crucial role in reducing fracturing costs and promoting waterless fracturing. Currently, the well-established methods for preparing LN_2 mainly involve air separation and refrigeration unit techniques. The air separation method involves compression, cooling, drying, and separation processes to obtain LN_2. On the other hand, the refrigeration unit method compresses nitrogen gas before cooling it through a refrigerator to produce LN_2. However, it should be noted that these devices require materials and designs capable of operating at low temperatures to prevent fracturing or damage, ultimately contributing to cost reduction in LNF. LN_2 possesses unique characteristics, including an ultralow temperature (−196 °C), a high compression ratio (1:696), a significant frost heaving force (up to 207 MPa), and low viscosity. Its exceptional compatibility with coal seams ensures that there is no reaction with the minerals present in the coal, and it also leaves no liquid residue after vaporization, thereby avoiding any reservoir damage associated with water sensitivity or water lock. [9]. Subsequently, McDaniel et al. [10] and Grundman et al. [11] attempted to use low-temperature-resistant glass-fiber oil tubing and stainless steel wellhead devices to inject LN_2 into coal and shale formations, which increased the reservoir permeability and daily production, demonstrating the feasibility of its use as a fracturing fluid for engineering purposes. Coetzee et al. [12] used LN_2 as a fracturing fluid for their study; under the action of LN_2, thermal stress can effectively promote the development and extension of microfractures or pores; King et al. [13] used liquid CO_2 for the reservoir penetration enhancement of dense sandstones and found that the original fissures would be expanded and new thermal stress fractures would be formed under the action of thermal stress formed by the ultralow temperature. Currently, injecting inert fluids (such as LN_2, liquid CO_2, and HP) into low-permeability reservoirs as an alternative to conventional hydraulic fracturing fluids to increase permeability has been widely applied in oil and gas wells. Currently, the injection of inert fluids (such as LN_2, liquid CO_2, and HP) into low-permeability reservoirs as an alternative to conventional hydraulic fracturing fluids to increase the permeability has been widely applied in oil and gas wells [14].

However, the large-scale field implementation of low-temperature hydraulic fracturing in low-permeability coal reservoirs has not yet been conducted, mainly because of the lack of technical and mechanistic research. Previous laboratory experiments have shown that after a rock is immersed in LN_2, its mechanical properties deteriorate, and a dense fracture network is generated, significantly improving the gas diffusion capacity and permeability (by 10–20 times). LN_2 also has the dual effect of pressurization and displacement, with broad application prospects [15,16]. Subsequent studies have indicated that factors such as the fracturing event number, fracturing time, water content, and reservoir temperature during the LNF process can significantly affect the reservoir transformation effect. The main reasons for the permeability increase due to fracturing in the LNF process include the water-ice phase change, the LN_2 phase change, phase change fracturing, and frost expansion fracturing [17]. Nevertheless, compared to the low-temperature freeze-thaw process, the LNF process is a more complex reservoir transformation process, involving both the fluid-fractured rock and the coupling effects of temperature conduction, differential deformation, phase change fracturing, low-temperature freezing-thawing, and expansion fracturing, as well as multiple field transformations and fracturing effects. This study provides a comprehensive overview of the fracturing and fracture propagation evolution processes associated with LNF in low-permeability reservoirs, investigating the underlying mechanism governing the fracture propagation under ultralow-temperature conditions and discussing the feasibility and mechanisms of low-temperature LNF. These findings offer valuable insights and ideas for advancing the engineering of low-temperature hydraulic fracturing technology for low-permeability reservoirs.

2. Process and Mechanism of LN_2 Fracturing of Low-Permeability Coalbeds

Using high pressure and large displacement, LN_2 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 (Figure 1): first, the high-pressure LNF of the coal in fluid form, similar to the hydraulic fracturing process, leads to the generation and expansion of the main fractures in the coal seam; second, the differential deformation and fracturing stage resulting from the thermal exchange between the low-temperature LN_2 and coal is a typical low-temperature freeze-thaw process, contributing to the formation of a microfracture network in the coal; and finally, the gas-phase fracturing and pressure-enhancing process caused by the phase transition expansion of LN_2 drives the displacement of CH_4 in the coal seam, similar to that in nitrogen-plugged wells, while simultaneously achieving the synergistic effect of reservoir pressure enhancement and permeability improvement through the displacement. The interaction and influence of these three stages determine the effectiveness of the low-permeability reservoir transformation.

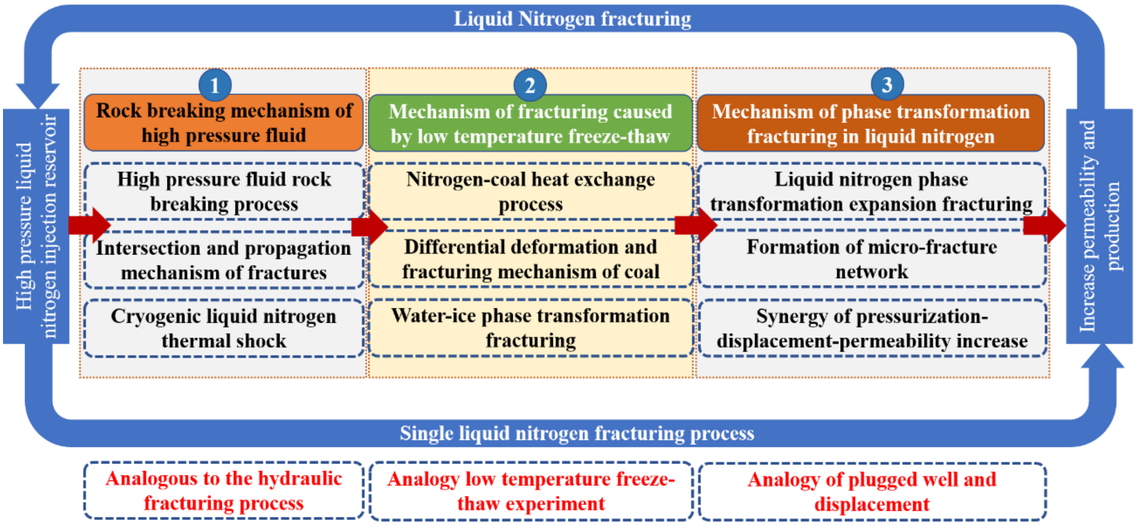

Figure 1. Mechanism of seepage enhancement via LNF of low-permeability coalbeds and associated effects.

2.1. Rock Breaking Processes with High-Pressure Fluids

The high-pressure fluid fracturing stage involves the entry of LN_2 into the coal fractures in fluid form (mainly liquid), fracturing the coal body like high-pressure water when the fracturing pressure exceeds the rock's mechanical strength. The premise and key to this process is that LN_2 under high pressure can exist in a fluid state in the coal wall. In 1756, Leidenfrost discovered that water droplets could float and roll on a sufficiently hot solid surface, a phenomenon known as the Leidenfrost phenomenon. The condition for this 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 rapidly boiling [18]. According to the temperature difference between the liquid and surface, boiling heat transfer can be divided into three categories: film boiling, which is the phenomenon of stable vapor film formation on a hot surface with a large temperature difference (Figure 2a, A,B); nucleate boiling, which involves bubble generation on a hot surface with a small temperature difference, in which the bubble generation rate is lower than the rate of the bubble detachment from the heated surface (Figure 2a, C–E); and transition boiling, which involves unstable vapor film formation on the heated surface when the bubble generation rate exceeds the rate of the bubble detachment from the heated surface (Figure 2a, B,C).

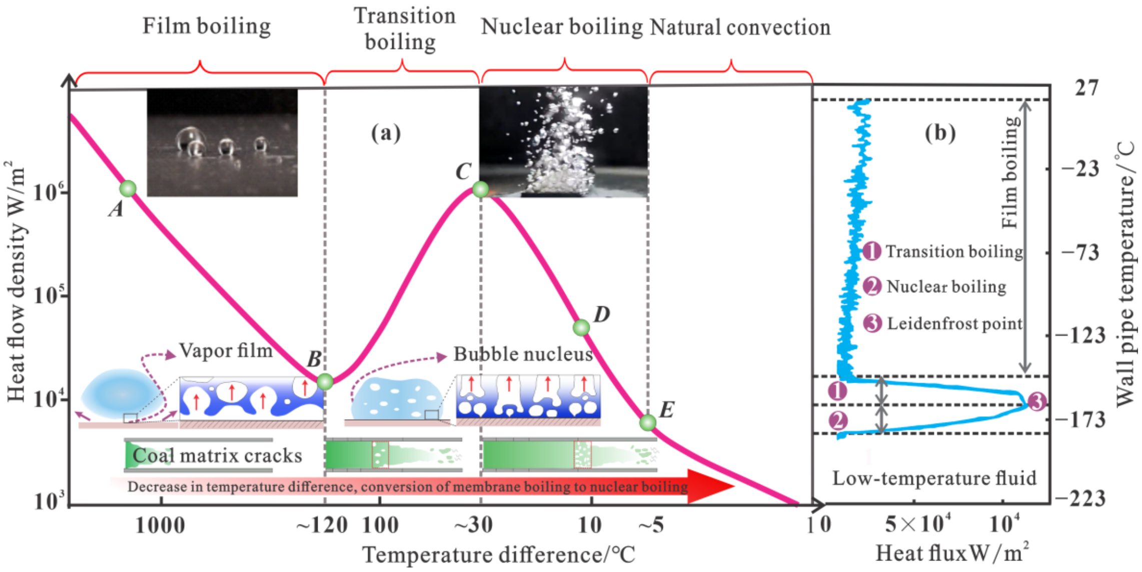

Figure 2. Heat exchange in the coal of the LNF process ((**a**) modified from Huang et al. [9], and (**b**) modified from Wang et al. [19]).

LN_2 itself has a very low temperature (−196 °C). When high-pressure LN_2 enters the coal seam (assuming that the coal seam is buried at a depth of 500–600 m, the temperature is approximately 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 significant temperature difference causes a substantial amount of LN_2 gasification on the fracture surface of the coal-rock; that is, the LN_2 and coal wall are covered by a steam layer (mainly nitrogen). The heat conduction between the LN_2 and coal wall is completed via conduction and radiation through the steam layer. The typical film boiling phenomenon involves heat exchange between the LN_2 and coal wall, which suddenly decreases the temperature of the LN_2 infiltration area, and nucleate boiling and natural convection boiling occur at this time. In general, the initial temperature conduction of LN_2 into coal is not as efficient as originally thought and is subject to the heat conduction process and the efficiency between the LN_2 and coal wall. Wang et al. [19] studied the change in the LN_2 phase state when LN_2 was introduced into a normal-temperature pipeline. The authors found that, at the initial time, because the wall temperature was much higher than the boiling point of LN_2, the front end of the pipeline was mainly characterized by film boiling. Over time, the wall pipeline gradually cooled, and the film boiling area 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 film boiling and nucleate boiling. The nucleate boiling area gradually increased after the LN_2 pipeline cooled (Figure 2); Darr et al. [20] calculated the evolution processes of the temperature and thermal convection density after LN_2 was continuously introduced into a pipeline. The authors found that the temperature decreased slowly in the film boiling state and decreased sharply in the nucleate boiling state, which also implied that the initial LNF stage exhibited more hydraulic fracturing behavior, whereas the later stage showed the heat exchange effect of temperature. Cha et al. [21,22] found that when sandstone was placed in LN_2 for a cold immersion experiment, it took up to 7 min for the sandstone to decrease from room temperature to the LN_2 temperature, and the temperature reduction rate was only 0.5 °C/s, which reduced the reservoir temperature more slowly. Coal is a reservoir with slower heat conduction than sandstone; therefore, the fluid state can be maintained for a long time after LN_2 is injected into the coal seam [23]. Wang et al. [24] and Li et al. [25] found that it takes a long time (even more than 40 min) for LN_2 to reach the equilibrium temperature, which provides a sufficient time guarantee for LN_2 to maintain liquid and high-pressure fluid fracturing, which is also the key to fluid fracturing.

Unlike conventional fracturing, LNF is a low-temperature fracturing process, which makes it unique. In the initial stage of fracturing, the temperature conduction may not be readily apparent. Similar to hydraulic fracturing, high-pressure fluid is primarily utilized for fracturing, followed by LN_2 to leverage its low-temperature fracturing characteristics, resulting in improved fracture creation effects at lower cycles and injection pressures. Hong et al. [26] studied the LN_2 process with the water-fracturing visual material PMMA (PolymethyI Methacrylate) and found that LNF significantly reduced the initiation pressure of the reservoir (a decrease of 47.1–71.7%), forming a complex fracture network characterized by a thermal stress fracture and main fracture. Some scholars have also pointed out that even a simple LN_2 cold shock and cooling process can generate a complex fracture system [27]. In this process, the fractures produced via the low-temperature fluid fracturing of coal and their relationship with the natural fractures determine the scale and complexity of the first fracture formation stage. In situ stress, the primary fracture scale, the angle between the new fractures and natural fractures, and their action processes are the main controlling factors [28].

2.2. The Low-Temperature LN_2 Freeze-Thaw Fracturing Process

In addition to fracturing the coal body, the pressing of high-pressure LN_2 into the coal seam is also accompanied by a wide range of subsequent effects, including the heat exchange process between the low-temperature fluid and the coal, the low-temperature freeze-thaw reaction, the frost heaving reaction caused by the water-ice phase transition, and the gas expansion deformation fracturing reaction caused by LN_2 gasification. These processes often interact with each other to form more complex deformation and fracturing processes, and liquid nitrogen cycle freezing-thawing (LNCFT) is an important factor that increases the fracturing effect in the fracturing process. The low-temperature phase transition process between LN_2 and the reservoir 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 LNF process of the first two processes is dominant.

2.2.1. The Temperature Exchange Process

The initial temperature exchange process refers to the temperature exchange and deformation between LN_2 and the coal wall after LN_2 enters the coal seam, including the temperature conduction mechanism and the coal shrinkage differential deformation. The temperature exchange method used in this process was heat conduction. Heat conduction is a heat transfer phenomenon that occurs when there is no macroscopic movement in the medium. When LN_2 contacts the coal surface, ultralow-temperature LN_2 quickly absorbs the heat on the coal surface and reduces the surface temperature [29]. From the perspective of molecular vibration, heat conduction between LN_2 and coal is realized via the vibration of the basic structural unit (BSU) of crystal-like coal, and natural convection occurs in the fluid owing to the density difference caused by the temperature gradient. This natural convection promotes the transfer from high-temperature to low-temperature fluids and continuously radiates electromagnetic waves. Heat conduction, convection, and radiation occur simultaneously during the low-temperature fluid fracturing process, which jointly promotes temperature exchange during the fracturing process and provides a basis for the detection of low-temperature conduction processes via infrared detection technology. Chu et al. [30] used infrared thermal imaging technology to study the temperature distribution characteristics of coal samples after LNCT, revealing the effect of temperature on the mechanical properties of the coal during LNCFT. Ma [31] detected the change in radiation temperature in the coal fracture process via infrared spectroscopy and found that the temperature change had a good linear positive correlation with the porosity and stress change in the coal body.

With the continuous exchange of LN_2 and coal energy, the surface temperature of the coal gradually decreased, and the temperature difference gradient between LN_2 and coal was reduced. A cooling zone formed on the rock mass surface until the heat flux exceeded the Leidenfrost temperature. Therefore, LN_2 in the coal fracture changed from the initial film boiling state to the transition boiling and nucleate boiling states. This process caused the temperature resistance of the steam cushion to disappear, and LN_2 changed from the fluid phase to the vapor-liquid mixed phase, resulting in a rapid increase in the heat convection on the coal fracture surface. This further accelerated the temperature exchange rate between the LN_2 and rock mass surface, resulting in a rapid decrease in the temperature of the coal (Figure 2b). Macroscopically, the low-temperature impact process degrades the mechanical properties of the rock mass and significantly reduces its compressive strength, tensile strength, and Young's modulus, thereby reducing its fracture pressure [32]. Taking LNF coal as an example, the uniaxial compressive strengths of coal samples after LN_2 treatment were reduced by 16.18–33.74%, and the axial peak stresses were reduced by 13–21%, showing obvious deterioration [33]. 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 instead extend along the areas with weak mechanical properties and more complex mineral compositions in the coal components, thereby forming a dense fracture network [34]. The main reasons are as follows: (1) The sharp temperature decrease leads to rapid shrinkage deformation between the different types of coal components and organic-inorganic structures. Owing to the difference in the shrinkage coefficients of different coals, deformation mismatch occurs and leads to the formation of shear fractures. (2) In a water-bearing reservoir, the rapid cooling process causes the pore water in the reservoir to freeze into ice and produce frost heaving stress (up to 207 MPa), thereby 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 remain a focus for future research, as does the interaction process mechanism under low-temperature conditions. In view of the different resistance effects between different rocks, owing to the influence of the rock compositions, structures, porosities, original temperatures, and other factors, the cooling efficiencies and fracturing effects of tight rocks, such as coal, shale, sandstone, and granite, are also different. With the exchange of the fluid and coal temperatures, the low-temperature fluid and rock surface eventually reach a state of thermal equilibrium. At this time, the temperature gradient and fracturing effect are no longer obvious, the heat conduction rate gradually slows down, and an energy exchange balance is maintained.

2.2.2. The Intermediate Freeze-Thaw Fracturing Process

The water-ice phase transition is considered the predominant factor that causes fracturing in the LN_2 low-temperature freezing-thawing process. During this process, the pore water freezes, resulting in the formation of ice lenses through hydrogen bonding between the four water molecules. In this study, these ice lenses induced an approximately 9% volume stress expansion (Figure 3). Consequently, coal fractures can also expand due to this phenomenon [35]. Numerous experiments have demonstrated that saturated coal samples exhibit significantly higher susceptibilities to low-temperature fracturing than dry samples [36]. Moreover, an increase in the water content leads to longer and denser coal fractures (Figure 3d–f), with saturated coal samples exhibiting much greater increases in new fractures compared to dry samples (by 10–20 times) (Figure 3a–c) [37].

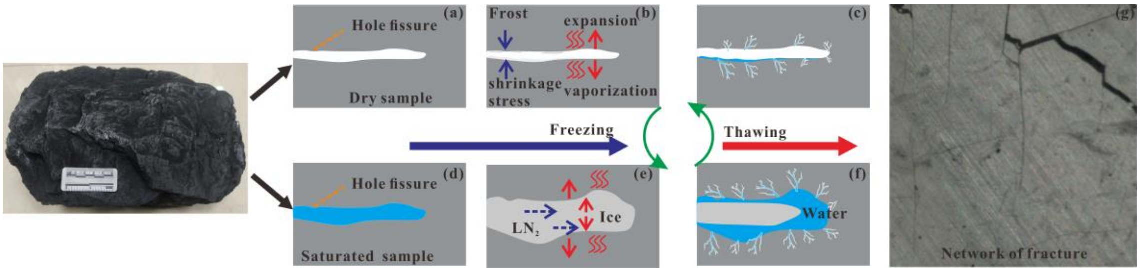

Figure 3. Pore change mechanism under LN_2 freeze-thaw action (**a**–**g**).

At present, most of the conclusions suggest that the low temperature of LN_2 causes water in the coal and rock pores and volume expansion (a volume increase of approximately 9%), which produce a substantial frost heaving force (more than 207 MPa) at the tip of the pore fracture, leading to fracture expansion [38]. Under the influence of siphons, the unfrozen free water migrates to the frozen area, and the extrusion stress generated by the frozen ice and free water increases the damage to the coal. However, this process needs to simultaneously satisfy the harsh conditions of space closure, high saturation, and a long freezing time, which are easy to achieve in the laboratory. However, it is not easy to maintain a sufficient freezing-thawing time or space closure under in situ conditions. More importantly, saturated water increases the frost heaving force but hinders the LN_2 migration channel, thereby affecting the subsequent temperature conduction process and fracturing effect. Recently, a study on the fracture mechanism of low-temperature rock masses in cold regions found that water will also form segregation ice in the fractures of low-temperature rock masses. Under the action of the segregation potential, the water in the unfrozen area migrates to the edge of the ice lens, leading to the ice lens's growth. The continuous growth of the ice lens and its squeezing of the fracture wall can also lead to rock fractures [39,40]. This discovery eliminates the need for a sealed space and saturated water in the water-ice phase transition, so that the microfracture rupture position is not only limited to the fracture tip but may also appear in any ice lens formation area (especially at the structurally weak plane position in coal). Is this the reason for complex fracture networks under saturated water conditions? Further research is required in this regard.

2.3. The Liquid-Gas Phase Change Fracturing Process

The temperature of LN_2 can be as low as −196 °C. After LN_2 is injected into the coal seam under high pressure, the temperature decreases and then recovers. LN_2 produces a strong vaporization phase change. An amount of 1 m^3 LN_2 can expand to 696 m^3 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, fracture expansion is difficult when relying solely on the LN_2 phase change. However, considering the deteriorating mechanical properties of coal and rock during the low-temperature freeze-thaw process, this possibility cannot be denied. In fact, the vaporization energy increase and adsorption expansion deformation in the LNF process 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 ultralow-temperature fluid and its deterioration of the coal strength; and second, the high-pressure fracturing and heat conduction effect caused by the phase transition process. These effects, such as gas expansion factors, have different degrees of influence on the integrity of the coal matrix and pore structure [41]. The experiment found that after injecting N_2 or CO_2 into the coal body, it had the fracturing function and increased permeability, pressurization, energy, and diffusion displacement [42,43]. The increase in the permeability and production after N_2 injection soaking also proves the influence of the phase change process on the coal structure [44]. The expansion deformation of coal occurs after gas adsorption and is positively correlated with the adsorption capacity, gas pressure, and carbon content and negatively correlated with the water content [41]. Although the expansion amount of N_2 and CH_4 mixed adsorption is less than that of pure CH_4 adsorption and is several times lower than that of CO_2 adsorption, considering the high liquid-gas ratio and low-temperature environment of LN_2, the strong vaporization pressurization and adsorption expansion deformation in the LNF process are much stronger than those of normal pressure adsorption expansion deformation. The superimposition of LN_2 high-pressure fracturing, thermal stress, and frost heaving forces is also a problem worthy of study.

In fact, during the process of LN_2 injection into coal, there is a change in the liquid, gas, and supercritical states. The energy conduction interaction between the multiphase fluid and coal involves the evolution coupling of the stress field, temperature field, and fracture field. Methods such as CO_2 phase change blasting, supercritical CO_2 fracturing, and low-temperature LNF all involve strong liquid-gas phase change processes, which have been widely studied considering the pore morphology and structural integrity changes in coal [43,45]. However, the change from the gas state to the supercritical state and its subsidiary effects need to be further studied. Plugging can further enhance the oil and gas recovery after fracturing. This technique not only offers the advantages of simplicity, cost-effectiveness, and environmental friendliness, but it also enhances the oil recovery, optimizes reservoir management, and extends the production cycles of oil and gas fields. It is worth noting that some fractures may be closed because of the formation pressure redistribution during the well plugging process. However, this closure is not entirely disadvantageous, as it contributes to the development of more intricate fracture networks that improve the fluid flow and the ultimate oil and gas recovery. Moreover, moderate fracture closure can reduce excessive liquid nitrogen loss, making the overall process more economical and efficient. Therefore, combining LNF with the closure effect presents a novel approach for enhancing oil and gas recovery. Although further research and optimization are required for the different types of oil and gas reservoirs in practical operations, this method has significant potential for future oil and gas exploitation applications.

3. Influencing Factors of the Low-Temperature Fluid Fracturing Effect

The factors affecting the low-temperature fluid fracturing effect on coal are complex and diverse and are generally divided into external factors (temperature difference, fracturing times, time) [46–51] and the internal factors of the coal itself (coal rank, water content, pore structure, mechanical properties of the coal body itself, etc.) [52,53]. However, studies have shown that low-temperature damage and expansion stress are the main factors that affect the LNF effect. The former can increase the matrix damage around the pore wall, provide the initial seepage path for fracturing, increase the fracture path expansion randomness, and improve the fracture network complexity. The latter promotes fracture initiation and continuous expansion by increasing the pore pressure. In an LNF experiment, freezing-thawing gave full play to the advantages of the former, and a higher temperature gradient expanded the advantages of the latter [54].

3.1. Effect of Temperature Difference on LNF

The rate of rock frost heaving and fragmentation is primarily influenced by the temperature difference. Low temperatures can exacerbate the rock damage and deteriorate the mechanical properties. A larger temperature gradient leads to increased anisotropic deformation between the minerals, making the rock more prone to breakage. Numerous scholars have conducted simulations on the impact of the initial rock temperature on the fracturing effects. Liu et al. [55] found that the thermal stress increased by 17% when the temperature gradient of the coal increased by 150 °C, which caused the initiation, expansion, extension, and expansion of the fracture network and significantly changed the fracture structure of the coal. Zhang et al. [56] found that with the increase in the initial rock temperature, the rock breaking volume and depth increased, and there was a key temperature range that promoted the sudden failure of granite: when the temperature difference was 450 °C, only weak damage occurred; when the temperature difference reached 670 °C, the rock mass quickly broke into two halves. Cai et al. [57] analyzed the breakdown pressure and fracture morphology of high-temperature granite at different heating temperatures. The results showed that the breakdown pressure of the granite decreased with the increase in the temperature gradient, and the failure mode was mainly tensile fracture. Based on the theory of trace elements and damage mechanics, Lin et al. [58] established a thermodynamic damage model of coal. Li [59] found that the higher the initial temperature of the coal sample, the greater the deterioration of the physical and mechanical properties of the coal sample, and the shorter the macroscopic failure cycle. Yan et al. [60] found that the prefabrication temperature of coal is positively correlated with its surface fracture propagation and internal damage. Some scholars have found that the thermal shock effect of LN_2 is selective in coal with different metamorphic degrees and that the fracturing effects of low-metamorphic and medium-metamorphic coal are higher than that of high-metamorphic coal [61].

Weathering and crushing occur at faster rates in alpine areas than in warm regions. During this period, the rock may not experience extremely low temperatures (such as −196 °C for LN_2) but rather undergoes repeated temperature fluctuations within a certain range (from 0 °C to −30 °C). This phenomenon suggests that low-temperature fracturing does not necessarily require the same temperature as LN_2 but only needs to surpass the critical fracturing temperature at a specific frequency to induce rock damage. Additionally, it has been observed that numerous fractures can be generated in tuff between −0.92 °C and −2.77 °C, in sandstone between −5 °C and −10 °C, and in granite between 0 °C and −1 °C. Below these temperature ranges, there is no significant acceleration in the fracture process [62], indicating that an absolute low temperature should not be a necessary condition for rock fracturing and that the repeated crossing of the critical fracturing temperature is the key to low-temperature fracturing [39,63]. How do the temperature distribution and conduction occur during in situ LN_2 injection? In which temperature range does the LN_2 fracturing efficiency reach its peak? Are these the next crucial issues to be investigated?

3.2. Effect of Moisture on LNF

In this study, we found that the ice-wedge expansion of saturated water under low-temperature conditions had the greatest impact on the destruction of the coal-rock joint structures. This is because the pore water becomes ice during the LN_2 freezing process, the volume expands, the pore pressure increases, and the internal pore structure of the rock is destroyed, resulting in stress concentration and fracture propagation [64]. For dry and low-water content coal, low-temperature freezing primarily plays a role in weakening the pore structure. However, when the water saturation of coal exceeds a certain critical value (e.g., more than 60%), the number of micropores in the coal shows a significant growth trend [65]. Notably, the size and number of microfractures in the LN_2-treated hydrous coal samples were significantly higher than those in the dry coal samples. This is because the low-temperature treatment of LN_2 not only aggravates the cold shrinkage effect of coal but also promotes the migration and redistribution of water in the coal, thereby inducing more microfractures. The formation of these microfractures not only enhances the permeability of the coal but also provides more favorable conditions for CBM exploitation.

Many researchers have studied the effects of LNF under various water conditions, finding that the effect of the LNF of coal is significantly correlated with the initial water content of the sample. The larger the initial water content, the greater the frost heaving force formed by water freezing and expansion and the more significant the fracturing effect. Wang et al. [66] found that, in the process of LNFT, the coal water content was positively correlated with its surface frost heaving force and porosity, and the coal permeability showed stage characteristics. Li et al. [67] found that, in the process of LNFT, the coal permeability increased exponentially with the increase in the water content. Dry coal samples mainly germinate new fractures based on primary pores, whereas water-bearing coal samples germinate new fractures, and, at the same time, the primary fractures are spatially connected to each other to form dense fracture networks. Li [68] put forward a similar point of view after the LNCFT of anthracite with different water contents, finding that the water in coal can promote the LN_2 fracturing effect. In addition, Qi et al. [69] also found that the mechanical properties of coal after LNCFT, such as the compressive density and elasticity, were weakened to varying degrees. Lin et al. [70] found that after LNCFT, with the increase in the water content of the coal, the widths of the surface fractures increased, and the ultrasonic wave velocity decreased significantly. Li et al. [71] determined the pore structures of dry and saturated coal samples after freezing-thawing and found that the water-ice phase transition in the saturated-water coal samples accelerated the temperature conduction in the coal, making them easier to fracture than the dry samples. Cai et al. [72] pointed out that, compared with the formation of only macroscopic fractures after the freezing-thawing of sandstone, coal samples form more complex fracture networks under LNCFT action, which is more suitable for the transformation of low-permeability coal seams. Our research group carefully designed the LNCFT test, conducted an in-depth study of the coal pore size distribution before and after the LNF, and confirmed that the coal water content can promote the LN_2 fracturing effect [61]. Although some progress has been made in the field of the LNF of coal, there are still many problems that require further study, such as the mechanism of the coal response to LN_2 with different saturation degrees and how the reservoir's water content adapts to the fracturing scheme.

3.3. Effects of Other Factors

(1) Mechanical deterioration. In the LNF process, the rock's physical and mechanical properties play an important role in the fracture formation and expansion, among which the strength parameters are particularly critical. The strength parameters include the compressive strength, tensile strength, and shear strength of the rock. When LN_2 is injected into the rock, its low-temperature effect forms a temperature gradient inside the rock and generates thermal stress, which has a significant impact on the coal fracturing process. Cai et al. [73] showed that the elastic moduli of dry coal samples decreased by 25% and the compressive strengths decreased by 34% after soaking them in LN_2. In other studies, the Young's moduli and compressive strengths of coal samples after freezing-thawing in LN_2 decreased significantly. Among them, different rock types showed obvious differences in the initiation points after the LN_2 injection. Cui et al. [74] found that the strength and stiffness of marine clay decreased by about 48.5% and 22.7%, respectively, through low-temperature freeze-thaw experiments. Liu et al. [75] studied the effect of freeze-thaw cycles on the consolidated soil matrix. Quan et al. [76] found that the resilient modulus of Qinghai-Tibet clay decreased with the increase in freeze-thaw cycles. Chang et al. [77] evaluated the shear strength of coarse-grained soil according to the freeze-thaw cycle. Memon [78] discovered that the nanoindentation modulus of Mancos shale samples was significantly affected by low-temperature LN_2. Applications of 50 mN and 200 mN resulted in decreases in the nanoindentation moduli of the Mancos samples from 24.6 GPa to 16.8 GPa and 15.6 GPa, respectively. Jin [79] conducted experiments on anthracite and coking coal using LNCFT, which led to reductions in the elastic moduli, compressive strengths, and brittleness

indexes of the coal samples after thawing, consequently changing their properties from brittleness to ductility. From the above analysis, it can be seen that multiple freezing and thawing can deteriorate the mechanical properties of coal rock, which lays the foundation for the generation and development of fissures in the subsequent stages.

(2) Coal structure. In addition, the rock's pore structure also affects the fracture initiation point of freeze-thawed coal via LN_2. The pore structure of the rock affects its physical properties, such as its permeability and elastic modulus, and then affects the LNF effect. Injecting LN_2 into a rock with a complex pore structure will lead to uneven LN_2 distribution in the rock, which will cause a difference in the thermal stress at different positions and subsequently affect the fracture formation and expansion. Qin et al. [80] studied the LNCFT effect on the physical pore and fracture structure of coal. The results showed that the elastic moduli of the coal samples decreased after freezing and thawing, while the porosities and Poisson's ratios showed upward trends, and the mechanical strengths decreased accordingly. In addition, the damage effect of cyclic freezing and thawing on coal is continuous and especially pronounced after 20 freeze-thaw cycles, and the failure rate is significantly increased.

The effect of LN_2 on coal fracturing is influenced by various factors, including the internal coal characteristics, such as the coal rank, mineral composition, and microstructure. The mineral composition and organic matter content of coal samples can affect the thermal expansion coefficient, thermal conductivity, and thermal shock resistance of the coal. Consequently, different degrees of damage and fracture may occur in distinct mineral particles during LNCFT, thereby affecting the growth rate and fracture areas of the internal fractures in the coal [81]. The reactions of different types of coal with LNCFT are also different. Generally, the fracturing effect on low-rank coal is greater than that on high-rank coal [82]. Qin et al. [69,83] used nuclear magnetic resonance (NMR) technology to observe the effects of lignite, bituminous coal, and anthracite before and after freezing and thawing with LN_2 for 60 min. The analysis found that lignite had the most significant LN_2 transformation degree of the different coal bodies, followed by anthracite and bituminous coal. The permeability improvement effect of the lignite under the influence of LN_2 was found to be the most pronounced, whereas the anthracite showed insignificant changes, as concluded by Lu [84]. Furthermore, our research reveals that the LN_2 fracturing effect on coal exhibits selectivity, with a more favorable outcome for lignite than for bituminous coal and anthracite. The key factor in forming a fissure network is the extension of the original fissures during the fracturing process [61].

(3) The number of LNCFT cycles and the freeze-thaw time. The external factors that affect the LNF effect on coal include the number of LNCFT cycles and the freeze-thaw time. Compared with a single freeze-thaw treatment, the multiple-fracturing process can gradually reduce the pressure required for reservoir fracturing and significantly improve the fracturing effect through the superposition effect [85,86]. Qin et al. [87] pointed out that, compared with a single LN_2 injection, the cyclic injection method has a better fracturing efficiency. Research by Zhai [88,89] showed that the freezing of LN_2 caused coal body damage, which promoted the formation of fractures, and that the degree of damage was positively correlated with the water saturation of the coal. Zhang et al. [56] found a single cycle of fractures with lengths of 80 mm after the LNCFT of coal samples with no obvious fractures on their surfaces. After three treatment cycles, the fracture lengths increased to 85 mm, and the permeability increased by 1129.79% compared with the original. Through cyclic freezing-thawing experiments, Ghobadi et al. [90–93] found that cyclic freezing-thawing aggravated rock damage, resulting in more significant mechanical degradation and permeability improvement. However, different scholars have different understandings of the LNCFT effects. Some scholars have pointed out that with the progress of the nitrogen cycle fracturing process, the LNCFT effect on the pore fracture transformation in coal is gradually weakened [94], which implies that there is an upper limit for the coal structure transformation in the cyclic fracturing process. For example, Zhang et al. [49]

found that after 240 h of LN_2 action, increasing the LN_2 action time had no effect on the fracturing effect.

4. Fracture Propagation Process and Fracturing Effect

4.1. Fracture Propagation Process under Low-Temperature Conditions

Currently, there is extensive discourse on the fracture propagation mechanism during hydraulic fracturing in low-permeability reservoirs. The interactive connectivity between hydraulic and natural fractures plays a pivotal role in fracture network formation. The characteristics (length, density, interval) and occurrence (dip, trend) of natural fractures significantly influence the extension and propagation of hydraulic fractures [95]. LNF engineering also involves the high-pressure fluid fracturing of reservoirs, which necessitates the interaction between natural and artificial fractures. However, ultralow-temperature fluid fracturing differs from traditional hydraulic fracturing because of its low-temperature thermal shock and uneven cooling process. Previous studies have indicated that significant temperature differences cause stress concentration in rocks, whereas repeated cold-hot cycles deteriorate the mechanical properties of coal. This leads to differential shrinkage among the minerals and structures within coal, resulting in the expansion and extension of the primary coal fractures, the surface shedding of coal particles, and the initiation and development of new fractures [37]. Following LN_2 transformation, coal fractures can be categorized into three types: extended fractures, intersecting fractures, and new fractures. The expansion and evolution processes of these fracture types differ under low-temperature conditions. Under dry conditions, natural fractures primarily undergo extension. The scale of the original fracture expansion and intersection determines the transformation outcome. Conversely, with increasing water contents in coal samples, new fractures and intersecting fractures become the dominant factors. The microfracture network formed via LNF is a consequence of the combined influences of the stress field-temperature field-fluid field interactions. During the fracturing process, both the fracture number and length significantly increased with multiple fracturing cycles, and a higher water content enhanced the fracturing effectiveness (Figure 4).

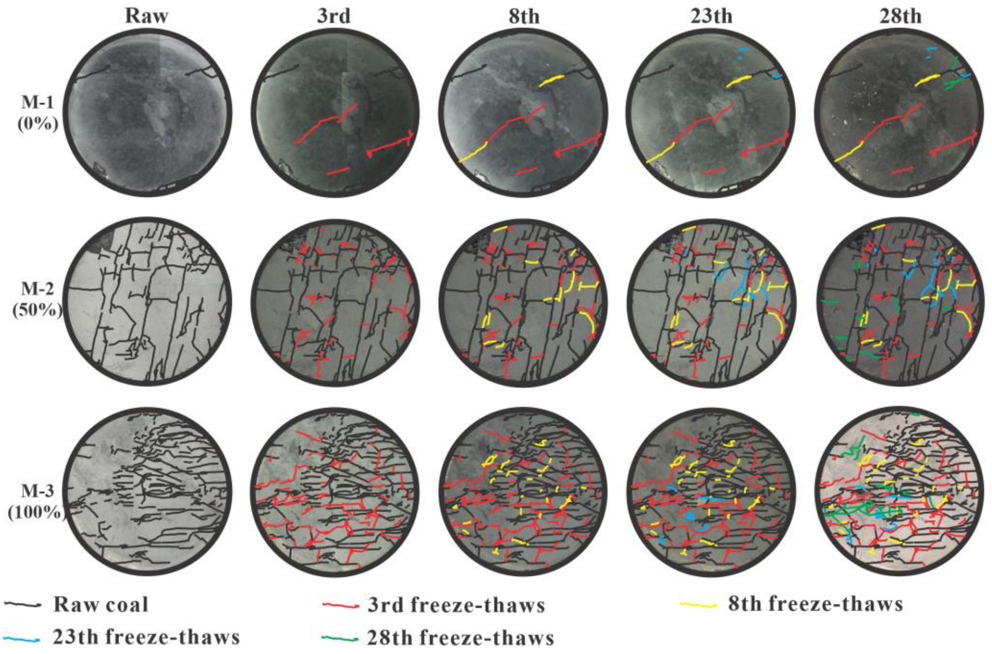

Figure 4. LNCFT fracture propagation evolution diagram (modified from Li et al. [37]).

The LN_2 fracturing process was staged and selective, with the strength of the initial transformation directly influencing the fracture transformation effectiveness (prior to eight cycles). By comparing and analyzing the LNF mode at low temperatures, it was observed that the fracturing process follows a pattern of rapid increase (Δh_1)—weak increase (Δh_2)—rapid increase (Δh_3)—weak increase (Δh_4)—(etc.) (Figure 5). Additionally, interphase circulation contributes to variations in the fracture parameters, such as the number, length, surface density, and porosity, resulting in sequences of rapid-slow-rapid increases during different stages. Furthermore, the Δh_i between the different cycles exhibits a decreasing trend, indicating a gradual weakening of the fracturing effects with the increasing number of cycles, emphasizing the significance of the initial fracturing effects on the subsequent outcomes.

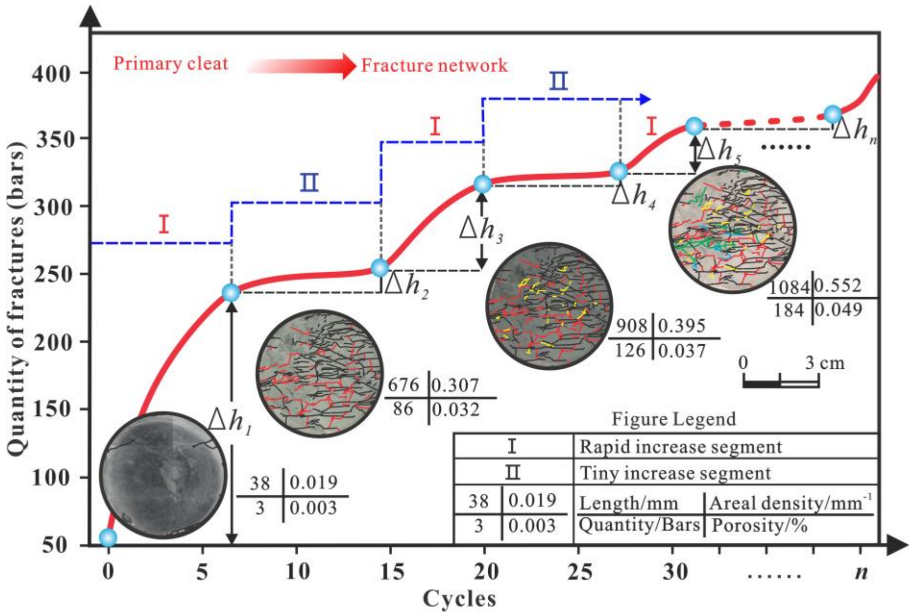

Figure 5. Evolution diagram of LNF effect stages (modified from Li et al. [37]).

4.2. Effect on Gas Migration Efficiency

An investigation of the gas migration rate in a rock fracture network under the influence of LNF elucidates the efficacy of unconventional natural gas development, encompassing the CBM production evolution and reservoir permeability. LNF technology, as an efficient approach for CBM exploitation, has a substantial impact on enhancing the gas migration efficiency. Coal fracturing facilitates the expansion of the original microporous structure and the formation of a more intricate fracture network, thereby reducing the airflow viscosity resistance and enabling enhanced gas passage through the coal seam. Simultaneously, macromolecular structural gases, such as CH_4, can be readily desorbed from the surface of the coal matrix and can enter the fracture system to participate in migration.

From a microscopic perspective, the thermal stress field generated during LNF is the primary driving force behind the evolution of rock microfracture networks. This process involves the breaking of weak bridge bonds in the coal molecules and the initiation and development of thermal fractures. The formation and expansion of these microfractures increase the connectivity between the pores and fractures, thereby improving the coal permeability. Zhao's research [96] highlights the crucial role played by micron-scale seepage pores and fractures in the overall permeability; despite accounting for a small proportion of the effective porosity, their contribution to the permeability is significant. The findings of Wei [97] indicate that hot-cold shock treatment has a more substantial fracturing effect than cold shock treatment, with an approximately ten times greater permeability increase. With the continuous evolution of the microfracture network, the initially relatively isolated pores undergo interconnection to form a more intricate seepage pathway, which plays a significant role in facilitating gas migration. Li [98] postulated that low temperatures and LN_2 vaporization induce expansion and frost heaving forces, promoting macro- and microfracture propagation and effectively enhancing the pore structure characteristics as well as the permeability of medium- and high-rank coal. Zhang et al. [7] observed a substantial increase in both the number and size of equivalent pores and throats in coal following LNF, resulting in an exponential increase in its permeability. Cai et al. [72] discovered that the rock mass permeability is enhanced while the wave velocity is reduced through the effective promotion of pore and fracture development via LNCFT. Su [99] further proposed that initial fracturing during cyclic LNF primarily extends along pre-existing fractures within the coal to establish a primary fracture network, with secondary fractures developing as the fracturing cycles progress.

Moreover, the mechanical properties of coal deteriorate to varying degrees after LNF, resulting in reductions in both the tensile and compressive strengths at the macro level. The change in the failure mode further complicates the section characteristics when the bedding angle varies, thereby affecting the gas flow characteristics. Specifically, when the bedding angle is 60°, the coal experiences the most significant decrease in tensile strength, which may lead to a substantial increase in the gas migration rate [100]. In addition, Yang et al. [101] discovered that the relationship between the growth rate of the permeability and treatment temperature follows an exponential function. Based on the SDR model, Xiao et al. [102] employed NMR technology to conduct a regression analysis on the permeability of coal treated with various fracturing variables. The findings revealed an exponential correlation between the coal permeability and the number of fracturing cycles, as well as a linear correlation with the fracturing time. Liu [103] emphasized that the shape factor of coal plays a decisive role in fluid migration under in situ conditions, while the fracture type resulting from LNF impacts the reservoir permeability. Our research group investigated changes in the coal permeability before and after LNF [37]. It was observed that the water-bearing samples exhibited significantly higher permeability growth rates following cyclic LNF than the dry samples, which were similar to the fracture development rates (Figure 6).

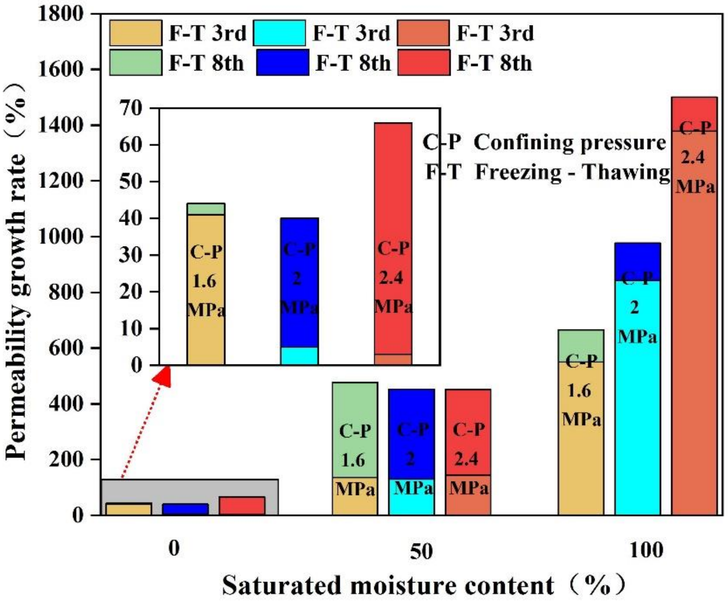

Figure 6. Coal permeability change trends with different water contents before and after LNF.

5. Feasibility Analysis

Based on the aforementioned analysis, ultralow-temperature fluid exhibits advantages in terms of its impact on the LNF and fracturing mode. However, despite being introduced as a technology in the 1990s, it has not yet gained widespread adoption, primarily because of the intricate technical constraints and economic costs. The selection of an appropriate fracturing mode plays a pivotal role in enhancing the adaptability and cost-effectiveness of the technology, which will be the main direction of cryogenic fluid fracturing in future research.

5.1. The Technology of LNF Low-Permeability Reservoir

The low-temperature characteristics of LN_2 are dual. On the one hand, it facilitates highly efficient low-temperature phase change fracturing; on the other hand, it poses challenges for field applications. Consequently, LNF technology is commonly employed as an auxiliary method and can be categorized into five main types: the cyclic injection of low- and high-temperature fluids; repeated LNF; LN_2 gas fracturing; LN_2-assisted fracturing; and LN_2 jet fracturing.

(1) The cyclic injection of low- and high-temperature fluids. The cyclic injection of low- and high-temperature fluids utilizes the principle of thermal stress fracturing in rocks based on temperature differences. The compressive strengths of coal and rock are reduced via the alternate injection of low- and high-temperature fluids, thereby enhancing the fracturing effect. In 1971, Tenneco Oil Company proposed LNF technology as an extension of conventional hydraulic fracturing [33]. The implementation process initially involves subjecting the reservoir to conventional hydraulic fracturing, followed by the injection of LN_2 as a low-temperature fluid to freeze the reservoir. Subsequently, when the temperature returns to the freezing point, high-temperature fluid is injected again, inducing thermal stress owing to the repeated temperature fluctuations that lead to fracture propagation in the coal.

(2) Repeated LNF. The technique of LN_2 refracturing relies on the influence of cyclic freezing and thawing to enhance the fracturing effect. In 1996, McDaniel and Grundman proposed the concept of cyclic fracturing using LN_2. They conducted a field experiment in Kentucky, USA, to investigate the effects of the freezing time and freeze-thaw cycles on a rock mass. Using tubing pumps and fracturing trucks, they injected a mixture of LN_2 and nitrogen into the formation. As a result, thermal stress and frost heaving caused the expansion of the existing fractures in the rock mass, leading to the development of an extensive fracture network [10,11]. Subsequent laboratory research has confirmed that LNCFT is an effective method for transforming low-permeability reservoirs; however, further verification is required for practical application in actual fracturing projects because of the high cost associated with the consumption of large amounts of LN_2. Determining the optimal number of fractures while maintaining high efficiency remains a challenge that needs to be addressed in future studies.

(3) LN_2-assisted fracturing. LN_2-assisted fracturing is an enhanced technique derived from conventional hydraulic fracturing that aims to optimize the effectiveness of hydraulic fracturing and boost production. This approach involves blending LN_2 with other fluids (e.g., water, nitrogen, or foam) to create a composite fracturing fluid. By reducing the viscosity and density of the fluids, LN_2 enhances the thermal and compressive stresses in rocks, while other fluids contribute additional effects, such as proppant transport, fluid recovery, and fracture cleanup. The applicability of this model varies depending on the fluid composition and the injection parameters for different rock types. In the 1990s, researchers successfully employed LN_2 to enhance unconventional oil and gas production via hydraulic fracturing [104]. For instance, in WLG05 at the Luling mine field in Huaibei, China, a water-based fracturing fluid combined with LN_2 was injected into coal formations at rates of 7.5 m^3/min and 0.3 m^3/min. After 15 days of plugging the well, full LN_2 diffusion into the rock resulted in increased permeability [105].

(4) LN_2 gas fracturing. LN_2 gas fracturing is a pressure technology accompanied by significant gas expansion. It has the advantages of a large compression coefficient, strong expansion ability, and high elastic performance. In 2011, Li et al. [106] proposed a LN_2 gas-fracturing technology for shale oil and gas storage. They suggested inserting double-layer insulated tubing into the casing, placing perforations between the tubing packers, and subsequently injecting pressurized LN_2 into the formation. During the initial stage, owing to temperature differences between the LN_2 and the formation, the rock

surrounding the wellbore contracts and becomes brittle, while the existing fractures expand and new fractures form. During the subsequent stage, the LN_2 evaporation causes fracture expansion under the increased gas volume pressure. This technique requires a substantial displacement capacity and rapid vaporization; further verification is needed regarding its effectiveness in enhancing the permeability of porous, low-permeability reservoirs.

(5) LN_2 jet fracturing. LN_2 jet fracturing is a method that utilizes high-speed jets and thermal shock, making it suitable for multibranch drilling operations. In 2018, Yang et al. [107] proposed radial abrasive LN_2 jet drilling (ALN-RJD), which combines high-speed jet impingement with thermal shock and gas fracturing. Radially injected LN_2 jets form a complex lateral fracture network with multiple branches from the main wellbore. Additionally, the jets can penetrate the rock to create a complex fracture network, which is particularly effective for hard and brittle rocks, such as granite and shale. This approach employs high-pressure LN_2 jets to initiate or expand rock fractures, while the low-temperature conditions alleviate the difficulties associated with rock breaking. However, LN_2 jets also increase the pressure exerted by the low-temperature fluids and present equipment challenges.

5.2. LNF Low-Permeability Reservoir Model

In contrast to conventional hydraulic fracturing, the fracturing process of an ultralow-temperature flow necessitates the consideration of the types and characteristics of low-permeability reservoirs. A comprehensive evaluation of the fluid phase state, thermal stress impact, heat exchange processes, and fracturing effects during operation is also required. Additionally, factors such as the LN_2 transportation, storage, and recovery need to be considered along with the technical and economic investments. The fracturing of low-permeability reservoirs using LN_2 is a complex undertaking that presents numerous technical challenges. The key aspects include layer selection, the fracturing parameter design, LN_2 injection equipment considerations, the implementation of the fracturing operations, fracture monitoring and evaluation techniques, safety measures for environmental protection purposes, and effect assessment and optimization [108]. First, an appropriate low-permeability coal seam is selected through detailed geological exploration and evaluation. The accurate design of the fracturing parameters ensures both effective results and safety precautions. Subsequently, the LN_2 injection equipment is prepared, and the construction commences with strict control over the injection parameters to ensure effective fracture expansion. Additionally, the appropriate pre-cooling of the equipment can be conducted prior to the construction to minimize economic losses.

In fact, there have been numerous successful instances of utilizing LN_2 for fracturing. Shouldice [109], inspired by the technical concept of LN_2-assisted drilling, employed self-pressurization to create an air cushion in the annulus through the vaporization of LN_2. This approach effectively mitigated abrupt pressure fluctuations and provided a certain level of casing protection. Tenneco Oil Company [110] utilized low-temperature fluid to modify target reservoirs by injecting it into underperforming injection and production well fractures, followed by high-temperature fluid injection to establish a complex network of seams adjacent to existing fractures. McDaniel et al. [10] implemented on-site construction using specialized low-temperature tubing and wellheads for four gas wells and one dense sandstone gas well, employing LN_2 as the fracturing fluid along with fiberglass tubing resistant to low temperatures for secondary fracturing enhancement. Grundman et al. [11] while utilizing fiberglass tubing and stainless steel wellheads, successfully applied LNF techniques in field operations targeting shale gas wells. These examples demonstrate the practical feasibility of LNF. However, in order to enhance its reliability, additional technologies such as real-time microseismic monitoring were incorporated to monitor fracture expansion and evaluate effectiveness. In recent years, microseismic monitoring technology for fracture evaluation has become a reliable tool in oil formation fracturing and production processes. As early as 1992, the Australian Federal Institute of Science and Industry conducted a series of studies on the mining-induced microseismic phenomena near coal faces [111]. Similarly, in 1997, in southeastern France, G. Senfaute et al. [112] utilized microseismic monitoring methods to analyze data from 2114 microseismic events in Provence coal mine. Simultaneously, safety and environmental protection measures are devised to guarantee construction safety. Regular evaluations are conducted to optimize the scheme and ensure the successful implementation and mining effectiveness of the LNF in low-permeability coal seams (Figure 7). The specific steps involved are as follows:

(1) LNF is suitable for reservoirs that are dry and water-sensitive, that are located in water-deficient, arid areas, that have high- and low-temperature gradients and low permeabilities, or that are not suitable for hydraulic fracturing.

(2) The drilling and perforation process involves inserting special stainless steel casings with low-temperature resistance into the wellbore from the surface to the fracturing layers. Free-hanging glass-fiber tubes are used to protect the casings from low temperatures. Double-layer casings are utilized at the wellhead to minimize the heat exchange between the LN_2 and casings. The cement slurry is injected through the casing and returns along the annulus through its bottom while the cuttings are being drilled. The cement then solidifies in the annulus to form a protective film, which allows drilling to continue until it reaches the target layer horizontally. After the completion of the drilling operations, the on-site disassembly of the drilling rig is followed by the cleaning of the wellbore using a mixture of water and gel injected by a workover rig [113].

(3) LNF engineering. The fracturing fluid is transported to the site by a LN_2 truck and mixed with the abrasives. The low-temperature fracturing fluid, which is mixed and pressurized by the truck, is then injected into the wellbore through a flexible pipe and directed towards the packer. Prior to the application of LN_2 for fracturing, it is essential to pre-cool the fracturing pipelines and wells. This can be achieved by utilizing thermally insulating glass-fiber oil pipes to minimize heat conduction, or by employing a double-layer casing [114] and annulus injection method [115] to pre-cool the pipelines, ensuring that the LN_2 remains in its liquid state during coal seam fracturing.

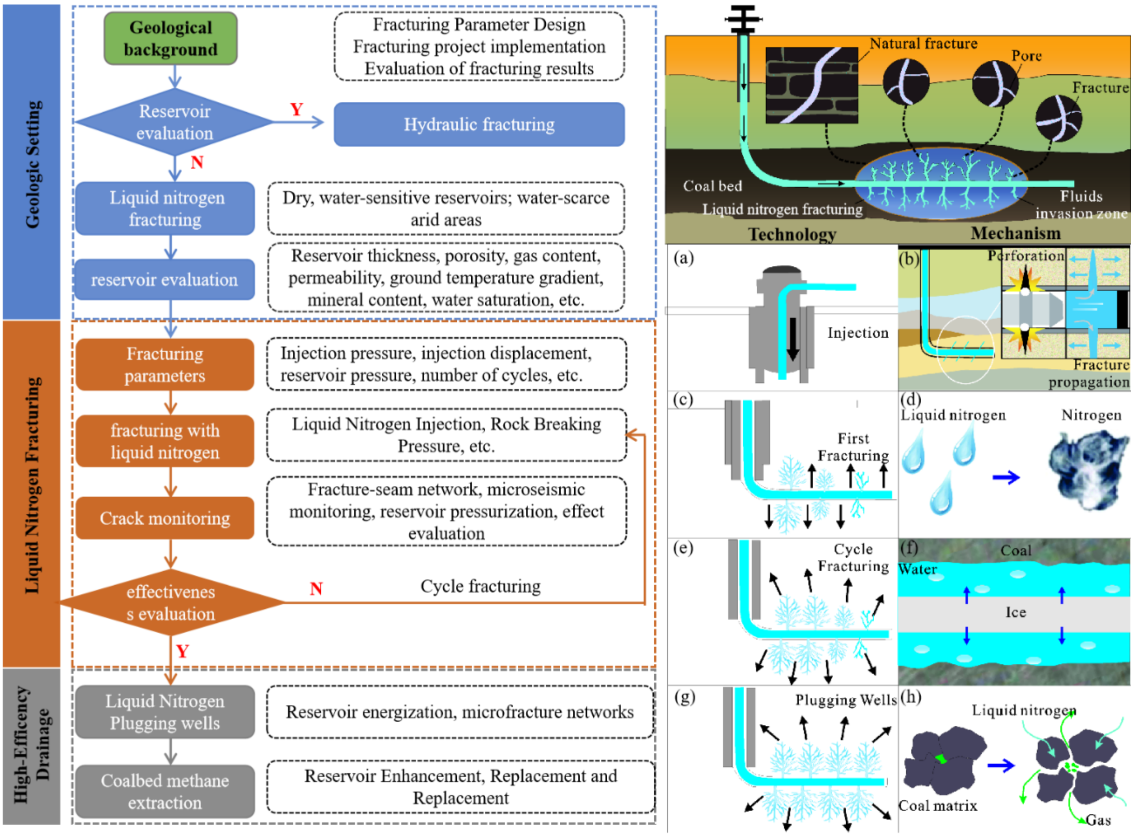

Figure 7. LNF technology and mechanism diagram (**a**–**h**).

Staged fracturing is conducted using a large-displacement, high-pressure approach to create a primary fracture network under the influence of low-temperature LN_2. By utilizing a proppant in a low-temperature fluid, an open fracture network is formed to facilitate CBM migration [116–118]. Microseismic and other monitoring technologies are employed during this process to track the fracture expansion and evaluate the effectiveness of fracturing operations. It should be noted that due to its low viscosity, LN_2 has a limited ability to carry proppant particles. To address this issue during actual fracturing operations, the pre-cooling of the equipment is necessary to increase the low-temperature fluid viscosity for effective proppant transport. Ultralightweight proppants are commonly used, such as resin-coated porous ceramsite or resin infiltration-coated walnut proppants. In the early stages of fracturing treatment, thickeners, such as guar-based fracture fluids, can be added in significant quantities to ensure the proper transportation of the proppants into the fractures while maintaining their openness throughout the treatment processes. This approach enhances the CBM flowability [119].

(4) The well plugging process following fracturing is implemented in different stages to achieve the "Fracturing + Plugging" mode for low-permeability reservoirs fractured by LN_2. By fully utilizing the low-temperature phase transformation process, the energy increase-displacement process is realized, leading to the expansion and extension of the primary fractures into a complex fracture network, thereby enhancing CBM production.

(5) Monitoring and dynamic analysis of LNF process. Pressure transient analysis (PTA) is a widely used method for fracture diagnosis and analysis. It involves solving the transient pressure at the bottom of the well to obtain logarithmic curves of pressure and derivatives, which are then used to invert values such as fracture length, fracture conductivity, and reservoir permeability through curve fitting methods [120]. In describing pressure transient analysis in fractured medium, various modeling methods are applied, with the Warren and Root model [121] being widely used in many reservoir types. Additionally, the distributed temperature sensor (DTS) is a permanent underground sensing tool that can be utilized for obtaining temperature data in the production casing [122]. Combining temperature monitoring with fracture expansion state monitoring can provide a more accurate simulation of a dynamic analysis of the reservoir fracturing process. Furthermore, when combined with microseismic monitoring for verification, the real-time evaluation of the fracturing effect and the optimization of fracturing parameters can be achieved.

6. Conclusions

In the present study, we delved into the application mechanism of LN_2 in the fracturing of low-permeability reservoirs and thoroughly discussed the factors influencing the fracturing effectiveness while also revealing its practical feasibility through real-world engineering applications. However, given the intricate formation structure in China, further enhancements in both equipment and technology are still imperative for LNF. The following conclusions can be drawn:

(1) LNF is the result of the synergistic effects of high-pressure fluid rock breaking, low-temperature freeze-thaw fracturing, and LN_2 phase change fracturing. The fracture formation during this process determines the complexity of the fracture network development. Low-temperature freezing and thawing with LN_2 involves temperature exchange and the water-ice phase transition induced by low temperatures. This process alters the internal stress structure of the coal, leading to fracture initiation and expansion. The LN_2 phase change fracturing process can be categorized into the vapor-liquid phase change and water-ice phase change. During this stage, the thermal stress and expansion stress resulting from the phase changes induce primary fracture initiation, propagation, and growth in the thermal stress fractures.

(2) The factors influencing the effectiveness of low-temperature LNF can be classified into internal and external factors, among which the coal moisture content and preset temperature have significant impacts. Notably, the water-bearing coal samples exhibited different fracturing mechanisms than the dry coal samples. The water-bearing coal samples

generated substantial thermal stress during the LNF processes. Moreover, large temperature differences can deteriorate the mechanical properties of coal while reducing the fracturing pressure. Therefore, higher water content levels combined with elevated preset temperatures favor more effective LNF outcomes.

(3) In this study, we elucidated the five LNF modes in practical industrial exploitation, analyzed their principles and field effects, and proposed suggestions for enhancing fracturing technology with regard to China's complex geological storage environment from the perspectives of the fracturing mode, fracturing agent, and proppant. These findings provide a reference and foundation for LNF engineering practice.

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Nomenclature

LNCFT	Liquid nitrogen cyclic freezing-thawing
LN_2	Liquid nitrogen
CBM	Coalbed methane
PMMA	PolymethyI Methacrylate
LNF	Liquid nitrogen fracturing
PTA	Pressure transient analysis
DTS	Distributed temperature sensor

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