

Article

Effect of Reservoir Transformation on Fracture Expansion in Deep Coalbed Methane Reservoirs and Mechanism Analysis

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Abstract: This paper proposed a fracture propagation model of water-based fracturing based on seepage–stress–damage coupling, which was employed to analyse the effects of different water-based fracturing fluid properties and rock parameters on the propagation behaviour of reservoir fractures in low-permeability reservoirs. Concurrently, molecular dynamics theory and mechanical analysis of reservoir fractures were employed to elucidate the microscopic mechanism of water-based fracturing on fracture propagation. The results showed that the apparent viscosity of water-based fracturing fluid primarily contributed to elevated fracture internal pressures through the seepage reduction in water-based fracturing fluid at the coal fracture surface. A substantial impact on the minimum fracturing pressure of coal fractures that rapidly pierce the coal rock and an increasing crack extension was notably presented by the low filtration and high viscosity of water-based fracturing fluids. Furthermore, the reservoir pressure and the crack turning angle were not conducive to the effective expansion of coal seam fractures, whereas the reservoir temperature exhibited a positive proportional relationship with deep coal seam fractures.

Keywords: low-permeability reservoir; water fracturing fluid; reservoir fracture propagation; petroleum engineering; unconventional energy



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1. Introduction

The repercussions of an energy deficit on the global economy were far-reaching and unavoidable, encompassing the economy, international trade growth, social stability, and environmental and energy policies [1,2]. In the short term, energy shortages resulted in reduced production, rising costs, and social instability [3,4], and the long-term energy shortages that are likely to ensue will also endanger the quality of life of residents and national energy security [5,6]. In the face of mounting resource scarcities, energy scientists and petroleum engineers have been compelled to explore the potential of alternative energy sources or the efficient use of fossil fuels, which were becoming increasingly limited in availability [7,8]. The present moment was characterised by a concerted effort among scientists to explore the discovery of new energy and unconventional energy, a subject that had recently given rise to a substantial corpus of research results. (1) New energy [9,10]. The development and adoption of new energy technologies are crucial for addressing global challenges such as climate change, energy security, and resource depletion. A plethora of supplementary energy sources, including renewable energy (e.g., solar energy, wind

energy) and several emerging energy technologies (e.g., nuclear fusion, hydrogen energy, etc.), were regarded as formidable competitors that are anticipated to supersede fossil energy [11,12]. However, it must be acknowledged that they were not without their defects and drawbacks. These included issues such as intermittent energy supply, high costs, resource dependence, environmental impacts, and social challenges [12,13]. These issues highlighted the need for continued innovation and investment in new energy technologies. Addressing these shortcomings necessitated a multifaceted approach, encompassing technological breakthroughs, supportive policies, international cooperation, and heightened public awareness [14–16]. It was only by surmounting these challenges that new energy sources could realise their full potential in powering a cleaner and more sustainable world [17]. Thus, the exploration and widespread application of new energy sources were contingent on the resolution of the aforementioned policy and technical challenges.

(2) Unconventional Energy. The term “unconventional energy extraction” refers to techniques employed to extract energy resources that cannot be accessed through conventional techniques [18–20]. These approaches frequently involved the exploration of challenging geological formations or the extraction of unconventional resources [21,22]. Examples included shale gas, oil sands, coalbed methane, gas hydrates, and deep geothermal energy. The exploration of these methods was driven by a multifaceted impetus, primarily the escalating global demand for energy, advancements in technology, and the strategic imperative to diversify energy sources [23]. Whilst these unconventional energy extraction methods showed the potential to expand the global energy supply and enhance energy security, they are also associated with significant disadvantages and drawbacks [24]. First, the water sensitivity of the working fluid during reservoir transformation can lead to the blockage of reservoir fractures, significantly reducing fracture permeability and impairing the efficiency of shale resource extraction [25]. Moreover, unconventional resources such as geothermal energy and hydrates are subject to geographic constraints, limiting their potential for development in certain areas [26]. Coalbed methane has attracted considerable attention from the scientific community as a potential unconventional energy source.

The majority of coalbed methane is stored in low-permeability deep coal seam, and the unique geological structure poses a significant challenge to reservoir transformation measures [27]. Fracturing technology, as one of the most commonly employed techniques for reservoir transformation, effectively facilitated the expansion of subsurface fractures and induced rock damage, playing a critical role in enabling the convergence and flow of the coalbed methane along the created fractures [28–30]. The contemporary domain of fracturing technology encompassed a diverse array of methodologies, including water-based fracturing technology, oil-based fracturing technology, foam fracturing technology, and CO₂ fracturing technology [31,32]. The employment of oil-based fracturing fluid has been demonstrated to have no deleterious effects on water-sensitive formations [33,34]. Furthermore, the efficacy of this fracturing fluid in reducing rock expansion, pore blockage, and stabilising reservoir permeability has been well documented. Nevertheless, the flammability of oil-based fracturing fluid posed a safety risk during storage and transportation [35]. The viscosity of oil-based fracturing fluid was highly sensitive to environmental factors, particularly temperature, which significantly influences the effectiveness of fracture propagation in coal seams and the uniform distribution of proppants within reservoir fractures [20,36]. The foam structure exhibits high viscosity and supporting power, which could effectively carry and suspend the proppant to achieve uniform support of the reservoir fracture [37]. However, the integrity of the foam fracturing fluid was susceptible to compromise when subjected to elevated temperatures and pressures [38,39], a phenomenon that adversely impacted fluid properties and the efficacy of the fracturing action [40,41]. Furthermore, an increase in operability led to a concomitant rise in the cost of foam fracturing. Simultane-

ously, CO₂ fracturing fluid displays low surface tension and high fluidity, which effectively carried proppants and helped to provide even support for coal fractures [42,43]. Nevertheless, a low CO₂ viscosity compromised the effective maintenance of fracture pressure, potentially resulting in inadequate fracture expansion capacity [44]. Water-based fracturing is considered to be an excellent reservoir reconstruction measure for low-permeability reservoirs and low-permeability coal seams [45], and water-based fracturing fluid achieved the fracture expansion in most geological reservoirs and reservoir convergence of coalbed methane. Nevertheless, the substantial filtration and inadequate temperature and shear resistance of water-based fracturing fluid in low-permeability deep coal seam served to curtail the expansion capacity of reservoir cracks [46]. Furthermore, the fracture propagation simulation of water-based fracturing technology was predominantly focused on conventional reservoirs (Table 1), and the water-based fracturing model of unconventional low-permeability deep coal seam has not been explored and analysed effectively.

Table 1. Research overview of on the water-based fracturing of coal seams containing coalbed methane.

Source and Author	Application Reservoir	Fracturing Model Theory
Li, Q, et al. [47]	Shallow high permeability coal seam	Shaped underground fracture theory
Yang, S, et al. [48]	Conventional coal seam (180 m)	Finite discrete element theory
Li, Y, et al. [49]	Shallow low porosity coal seam	Stress model of pulse fracturing in coal seams
Wei, J, et al. [50]	Shallow coal seam mining under the gully	Fluid-structure fully coupled 2D Finite element model

Herein, this paper proposed a water-based fracturing fracture propagation model based on seepage–stress–damage coupling, with a view to analysing the influence of many factors on the fracture propagation behaviour of unconventional low-permeability deep coal seam. Concurrently, the fracturing propagation criteria and rock damage criteria are utilised to evaluate and analyse the mechanical analysis of fracture tips and the evaluation of fracture initiation behaviour of water-based fracturing fluids in low-permeability reservoirs. Ultimately, the fracture and seepage mechanisms of water-based fracturing fluid in low-permeability deep coal seam are revealed by molecular dynamics models, microgrid models, and mechanical analysis. The novelty of this study lies in the incorporation of a seepage–stress–damage coupling model to analyse fracture propagation and coalbed methane extraction in low-permeability coal seams. Additionally, a chemical kinetics model for water-based fracturing fluid is introduced to elucidate the fracture propagation mechanism in coal seams. The construction of a fracture extension model of low-permeability coal seam rocks can serve as an effective method for the development of coalbed methane in reservoirs. Furthermore, the fracturing extraction of coalbed methane has been demonstrated to provide robust protection for national energy security.

2. Materials and Methods

2.1. Solid-Phase Governing Equations

The coal seam is regarded as a three-dimensional solid Ω , with a fracture surface designated as Γ_s . The tensile force F is applied to the outer boundary, denoted as Γ_h , of the aforementioned three-dimensional solid Ω . Furthermore, it is assumed that the application of the tensile force occurs within the quasi-static loading process. The solid phase control equation of the low-permeability deep coal seam can be expressed as shown in Equation (1).

$$\begin{aligned} \nabla \times \sigma + \rho b &= 0 & \text{in } \Omega \\ \sigma \times v &= h & \text{in } \Gamma_h \end{aligned} \quad (1)$$

where v is the unit normal vector of the outer boundary Γ_h , m/s. ρ is the density of reservoir coal seam, kg/m³. b is the physical strength of reservoir coal seam, N/m³. h is the normal load acting on the outer boundary Γ_h , N/m. Ω is the area of the computational domain, dimensionless. σ is the stress tensor, Pa.

The water-based fracturing process of low-permeability deep coal seams must ensure that the external loads are equal on both sides of the fracture surface, as illustrated in Equation (2) [51].

$$-\sigma \times n = \sigma \times n^- = p \quad \text{in } \Gamma_s \quad (2)$$

where n is the unit normal vector of local fracture surface in low-permeability deep coal seam, dimensionless. p is the pressure of the water-based fracturing fluid acting on the fracture surface, Pa.

Additionally, the displacement field u^h in the reservoir coal seam Ω can be decomposed into a continuous displacement field $\bar{u}$ and a discontinuous displacement field $\tilde{u}$, which can effectively characterise the strong discontinuities in displacement across the coal seam fractures.

$$u^h(x) = \bar{u}(x) + \tilde{u}(x) \quad (3)$$

The displacement difference between the positive $u^h(x^+)$ and negative sides $u^h(x^-)$ of the local crack surface is termed displacement discontinuity w , as demonstrated in Equation (4).

$$w = u^h(x^+) - u^h(x^-) \quad (4)$$

The surface energy G_s of the fracture surface of the reservoir coal seam can be calculated and analysed using Equation (5).

$$G_s = \int_{\Gamma_s} p \times w d\Gamma \quad (5)$$

Thus, the weak form of the solid phase governing equation can be obtained by cross-linking the aforementioned formulas (Equation (6)).

$$\int_{\Omega} \delta \varepsilon^T \times \sigma d\Omega = \int_{\Omega} \delta u^T \times b d\Omega + \int_{\Gamma_h} \delta u^T \times \bar{t} d\Gamma + \int_{\Gamma_s} p \times w d\Gamma \quad (6)$$

2.2. Fluid-Phase Governing Equations of Water-Based Fracturing Fluid

The mass balance equation for the fluid flow of water-based fracturing fluid can generally be described and analysed according to Equation (7) [52].

$$\frac{d}{dt} \int_{V_n} M^\kappa dV_n = \int_{\Gamma_n} F^\kappa \cdot n d\Gamma_n + \int_{V_n} q^\kappa dV_n \quad (7)$$

where V_n is the any sub-area of the fluid system of a water-based fracturing fluid. Γ_n is the closed boundary surrounding V_n . M^κ is the mass per unit volume of component κ , m³. F is the mass flow rate of water-based fracturing fluid, m³/min. q is the point sources and sinks within V_n . n is the normal vector of any small area $d\Gamma_n$ on Γ_n , and n points to the interior of Γ_n .

The unit volume mass M^κ can be calculated and solved according to Equation (8) [53].

$$M^\kappa = \sum_{\beta} (\phi S_{\beta} \rho_{\beta} X_{\beta}^{\kappa}) + (1 - \phi) \rho_R \rho_l X_l^{\kappa} K_d \quad (8)$$

where ϕ is the porosity of deep coal seams, %. S_β is the water saturation of deep coal seams, %. ρ_β is the water density in coal seam fractures, kg/m³. X_β^κ is the mass fraction of other substances (cross-linking agents) in water-based fracturing fluid, %. ρ_R is the density of coal seam rock skeleton. K_d is the distribution coefficient of water in coal seam rocks.

The flow rate of water-based fracturing fluid in coal seam rock can be calculated by the multiphase formula of Darcy's law (Equation (9)), which is principally employed to analyse the seepage and filtration of water-based fracturing fluid.

$$F_\beta = -\frac{kk_r\rho_\beta}{u_\beta}(\nabla P_\beta - \rho_\beta g) \quad (9)$$

where u_β is the darcy velocity of water-based fracturing fluid in coal seam rocks, m/s. k is the permeability of low-permeability deep coal seams. k_r is the relative permeability. u_β is the dynamic viscosity of water-based fracturing fluid in coal seam fractures, mPa·s. g is the gravity acceleration, and P_β is the internal pressure of water-based fracturing fluid in coal seam fractures, Pa.

In addition to the seepage of water-based fracturing fluid within low-permeability coal seam fractures, fluid diffusion also plays a significant role in the maintenance and propagation of internal pressure within these fractures. The diffusion equation governing the movement of water-based fracturing fluid in low-permeability coal seam fractures can be expressed by Equation (10) [54].

$$f_\beta^\kappa = -\rho_\beta d_\beta^\kappa \nabla X_\beta^\kappa \quad (10)$$

where d_β^κ is the diffusion coefficient of cross-linking agent in water-based fracturing fluid, m²/s.

2.3. Rock Cracking Theory of Low-Permeability Coal Seams

Numerous factors, including the properties of the fracturing fluid, the magnitude of the ground stress, and the heterogeneity of the rock, can significantly influence the initiation and propagation of cracks in coal seams during water-based fracturing. Traditional fracture mechanics and continuum mechanics characterise fracture initiation pressure as a function of the applied stress and the tensile strength of the rock. The fracture surface of low-permeability coal seams typically initiates along the direction perpendicular to the minimum principal stress, a phenomenon that can be quantitatively described by the reservoir fracture initiation pressure given in Equation (11) [55].

$$P_B = 3\sigma_h - \sigma_H + \sigma_t - P_p \quad (11)$$

where σ_h and σ_H are the minimum and maximum horizontal principal stresses in low-permeability coal seams. σ_t is the tensile strength of low-permeability coal seams, and P_p is the pore pressure of low-permeability coal seams.

The fracture initiation pressure is subject to modification by natural pore pressure or fluid penetration into low-permeability coal seams, as illustrated in Equations (12) and (13).

$$P_B = \frac{3\sigma_h - \sigma_H + \sigma_t - 2\eta P_p}{2(1 - \eta)} \quad (12)$$

$$\eta = \frac{\alpha(1 - 2\nu)}{(1 - \nu)} \quad (13)$$

where α and ν are the Biot's constant and Poisson's ratio.

2.4. Crack Propagation Criteria of Low-Permeability Coal Seams

The direction in which rock fractures expand in low-permeability deep coal seams is a significant prerequisite for fracture expansion, which is of considerable importance for the exploitation of coalbed methane in low-permeability coal seams. The maximum circumferential stress criterion is utilised to analyse the propagation direction of reservoir fractures (Equation (14)) [56].

$$K_I \sin \theta_0 + K_{II}(3 \cos \theta_0 - 1) = 0 \quad (14)$$

where K_I and K_{II} are the stress intensity factor of type I and the stress intensity factor of type II. θ_0 is the fracture extension angle of low-permeability coal seams, °.

K_I and K_{II} can be solved by Equations (15) and (16) [57].

$$K_I = \sqrt{\frac{2\pi}{r_m}} \left(\frac{\mu}{\chi + 1} \right) \Delta v \quad (15)$$

$$K_{II} = \sqrt{\frac{2\pi}{r_m}} \left(\frac{\mu}{\chi + 1} \right) \Delta s \quad (16)$$

$$\mu = \frac{E}{2(v + 1)} \quad (17)$$

where E and v are the Young's modulus (MPa) and Poisson's ratio. χ is the Kolosov constant. Δv and Δs are the displacement difference from the tip (r_m) of the coal seam fracture (extension distance).

The maximum circumferential stress criterion (Equation (14)) can also be simplified to Equation (18).

$$\tan\left(\frac{\theta_0}{2}\right) = \frac{1}{4} \left[\frac{K_I}{K_{II}} - \operatorname{sgn}(K_{II}) \sqrt{\left(\frac{K_I}{K_{II}}\right)^2 + 8} \right], \quad -\pi \leq \theta_0 \leq \pi \quad (18)$$

The determination of the crack propagation direction serves as a prerequisite for evaluating whether the points along the propagation path satisfy the crack extension conditions. In this study, the criterion for crack propagation in coal seams is based on the condition that the minimum principal stress is greater than or equal to the tensile strength of the reservoir rock (Equation (19)).

$$\sigma_{\max} \geq \sigma_t \quad (19)$$

In addition, the damage variable D is utilised to analyse and describe the degree of rock damage in low-permeability deep coal seams (see Figure 1). Furthermore, the isotropy of coal seam rocks can be demonstrated and evaluated using the damage variable D (Equations (20) and (21)).

$$\begin{aligned} D &= 0, & \zeta_{c1} < \zeta \\ D &= 1 + \frac{\sigma_{cr}}{\zeta E_0}, & \zeta \leq \zeta_{c1} \end{aligned} \quad (20)$$

$$\begin{aligned} D &= 0, & \zeta < \zeta_{t1} \\ D &= 1 - \frac{\sigma_{tr}}{\zeta E_0}, & \zeta_{t1} < \zeta \leq \zeta_{t2} \\ D &= 1, & \zeta_{t2} \leq \zeta \end{aligned} \quad (21)$$

where ζ_{t1} and ζ_{t2} are considered the ultimate elastic tensile strain and ultimate tensile strain of coal seam rock materials, respectively. ζ_{c1} presents a compressive strain in ultimate

elastic tension. Simultaneously, ζ_{tr} and ζ_{cr} are the residual tensile strength and uniaxial residual compressive strength.

Reservoir material that does not exhibit any fracture extension or coal rock damage is designated as $D = 0$, whereas complete fracture extension of coal rock leads to $D = 1$.

The estimation of the pressure at which rock damage and material failure occur in low-permeability coal seams can be facilitated by utilising Equation (22).

$$P_f = 3\sigma_h - \sigma_H - eP_p + \sigma_t \quad (22)$$

where P_f presents the damage pressure of low-permeability coal seams, and e is considered as an effective stress coefficient.

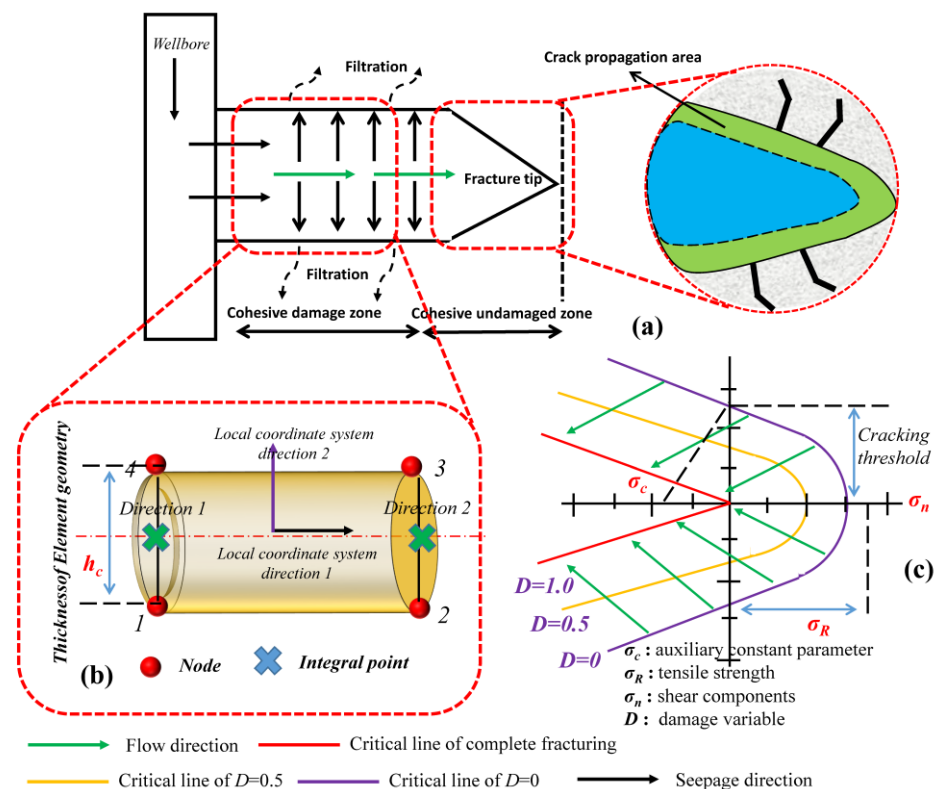


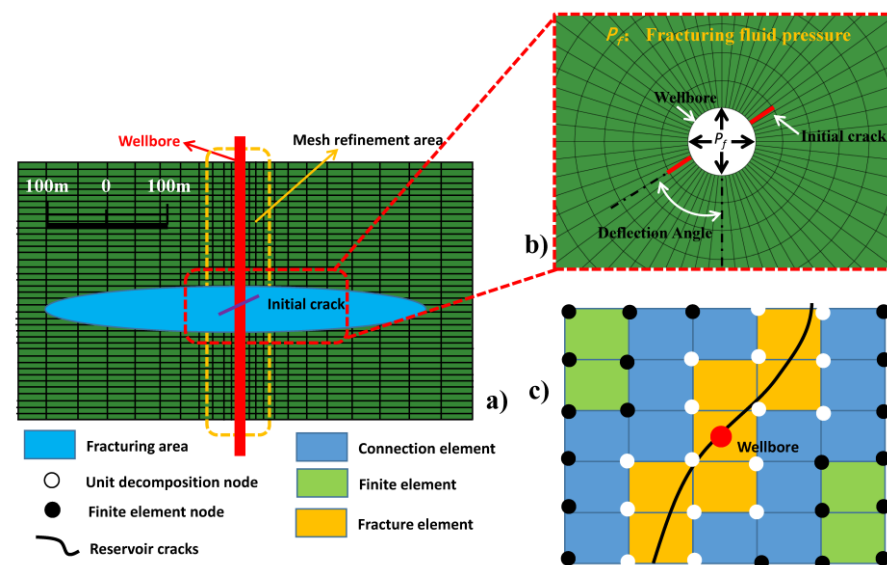
Figure 1. Fracture propagation behaviour of water-based fracturing fluid in low-permeability coal seams (a), fluid flow (b) and stress analysis (c).

2.5. Water Fracturing Model of Low-Permeability Coal Seams

A water-based fracturing fracture propagation model based on seepage–stress–damage coupling was constructed to explore the fracture propagation behaviour of low-permeability deep coal seams. The coalbed methane present within the low-permeability coal seam can be collected in the expanded fractures, thereby increasing the extraction recovery of coalbed methane. A 2D plane strain model with 15,000 mesh elements was developed, and the geological parameters of the low-permeability coal seams of the Ordos coal seam are listed in Table 2. Additionally, the fracture strain model of the horizontal well constructed in this study refined the grid in the proximity of the wellbore, thereby enhancing the convergence and stability of the model operation. Concurrently, initial fractures were set in opposite directions near the wellbore, thereby achieving fracture initiation and initial damage to the reservoir rock (Figure 2). It has been demonstrated by preceding studies [58] that wellbore mesh refinement is capable of delivering both stability and effectiveness in enhancing the convergence of model operation.

Table 2. Geological parameters of the low-permeability coal seams of the Ordos coal seam.

Parameter	Value	Parameter	Value
Elastic Modulus, E /GPa	20–35	Poisson's ratio, ν	0.20–0.30
Minimum horizontal principal stress, σ_h /MPa	30	Maximum horizontal principal stress, σ_H /MPa	40
Tensile strength, C /MPa	5	Initial pore pressure, P_p /MPa	25
Initial porosity, ϕ /%	6	Permeability, $\times 10^{-16}$ K/m ²	8
Leak-off coefficient	2.2×10^{-12}	Total fracturing time, T /min	9

**Figure 2.** Water-based fracture propagation model (a,b) based on seepage–stress–damage coupling (c) in the low-permeability coal seam.

3. Results and Discussion

3.1. Influence of Cross-Linker Content of Water-Based Fracturing Fluid on the Fracture Expansion

It has been demonstrated by preceding studies that the fracture propagation of CO₂ fracturing fluid in unconventional low-permeability reservoirs is influenced by CO₂ thickeners. Furthermore, the apparent viscosity of the fracturing fluid exerts a significant effect on fracture propagation and fluid behaviour (filtration or seepage). Figure 3 provides a more detailed analysis of the effect of the amount of additives (cross-linking agents) added to the water-based fracturing fluid and the fluid viscosity on the fracture propagation behaviour of low-permeability coal seams. Furthermore, the relationship between the fluid filtration and seepage behaviour of the water-based fracturing fluid in the reservoir fractures and the cross-linking agent content is also discussed in detail in Figure 3. A strong positive correlation exists between the cross-linking agent content and the fluid viscosity of water-based fracturing fluids, indicating that the incorporation of cross-linking agents enhances the viscosity of these fluids. Furthermore, when the cross-linking agent content exceeds 0.2 wt%, the rheological parameters of the water-based fracturing fluid experience a significant increase. In contrast, lower cross-linking agent concentrations do not produce substantial changes in the fluid properties. The increasing viscosity of water-based fracturing fluid also shows a positive impact on the propagation parameters of reservoir fractures, which can be proved and analysed by Equation (23) [13].

$$q = \frac{w^2}{12\mu} \nabla p \quad (23)$$

where q is the density vector of water fracturing fluid, m/s. w presents the fracture extended parameters, m.

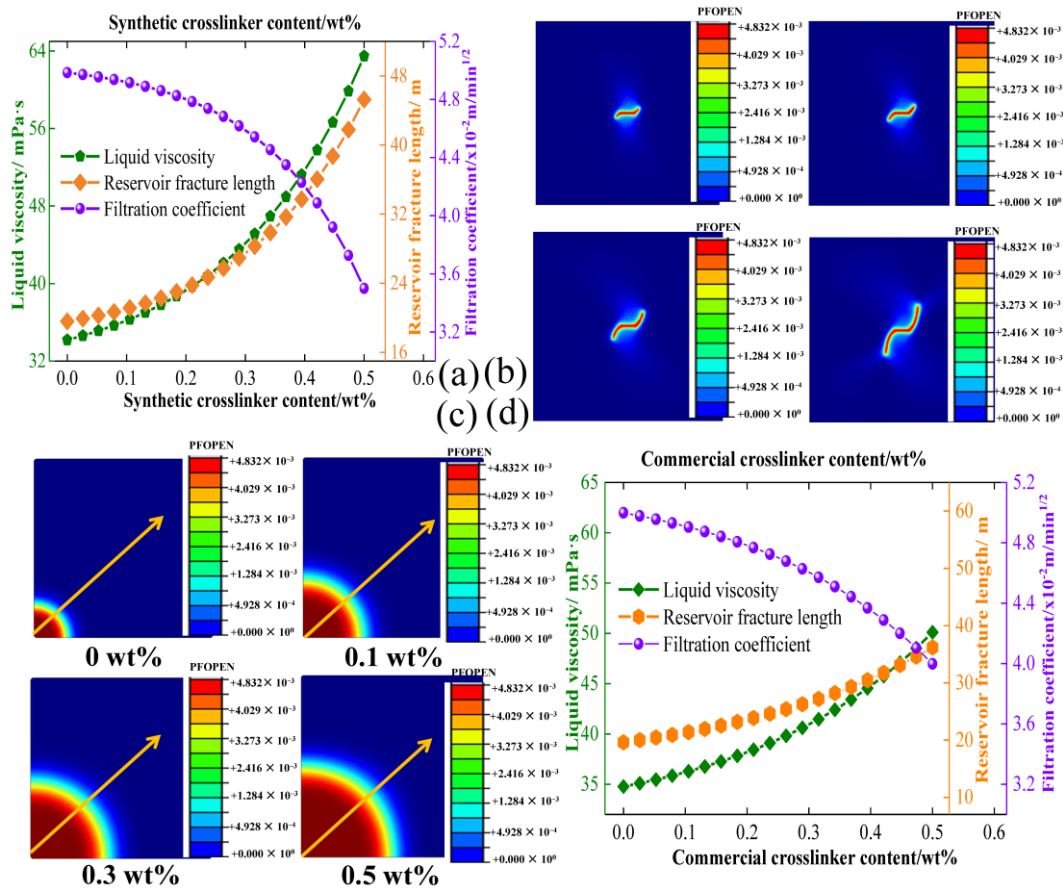


Figure 3. The positive relationship among the cross-linking agent content, fluid viscosity (a,d), coalbed methane extraction efficiency (c) and fracture extension length (b), and inverse relationship among the cross-linking agent content, the filtration coefficient of the water-based fracturing fluid at 20 MPa, 45° of turning angle and 180 °C.

A proportional relationship between the viscosity of the water-based fracturing fluid and the fracture expansion capacity at a constant flow rate q was demonstrated in Figure 3a,d, and the experimental data obtained in Figure 3a,d above are completely consistent with the fracture expansion w and fluid viscosity shown in Equation (23). Concurrently, the fluid viscosity of water-based fracturing fluid was a macroscopic manifestation of the hydrogen bonds [59] between molecules, and the pressure difference Δp in Equation (23) is formed by the increased fluid viscosity producing a smaller seepage. Water-based fracturing fluid without a cross-linking agent (0 wt%) will not cause the hydroxyl (OH) in guar gum to form obvious hydrogen bonds with water molecules, and more free guar gum molecules will appear in the aqueous solution [60]. At the same time, water-based fracturing fluid without cross-linking agent will not form dense intermolecular hydrogen bonds and microscopic lattices, which directly results in the macroscopically smaller fluid density of water-based fracturing fluid in coal seam fractures. A significant number of free molecules, generated by the lower fluid viscosity, can permeate into the coal seam rock through the pores on the surface of the coal seam fractures, leading to substantial filtration of the water-based fracturing fluid. Simultaneously, the fluid pressure ∇p within the reservoir fractures, which continuously decreases due to fluid seepage, fails to overcome the principal stress required to induce damage to the reservoir rock, thereby directly inhibiting the expansion rate and behaviour of the reservoir fractures [61]. The incorporation of

cross-linking agents into water-based fracturing fluids leads to the formation of hydrogen bonds between the polar groups of the cross-linking agents and the water molecules, as well as the establishment of intermolecular hydrogen bonds between the hydroxyl groups (OH) on the guar gum and the polar groups of the cross-linking agents. This mediating effect of the cross-linking agents facilitates the interconnection of numerous molecules within the water-based fracturing fluid, resulting in an increase in the microscopic grid density and an enhancement of macroscopic viscosity. Furthermore, the addition of cross-linking agents reduces the fracture seepage of free molecules in the water-based fracturing fluid, thereby preventing the significant filtration of fracturing fluid into the reservoir rock. The rapid increase in pressure within the fracture helps the water-based fracturing fluid overcome the initiation pressure of the reservoir rock, promoting fracture expansion. Thus, the incorporation of cross-linkers into water-based fracturing fluids has been demonstrated to stimulate the expansion behaviour of coal seam fractures in two primary ways: (1) Fluid filtration and seepage. The cross-linker entraps a substantial quantity of free water within the water-based fracturing fluid, thereby becoming an integral component of the microscopic grid, which leads to a direct reduction in the number of free water molecules and fluid filtration. (2) Cross-linkers have been shown to influence pressure within the fracture. In the absence of cross-linkers, water-based fracturing fluids permit the seepage of a substantial quantity of free water molecules into the rock on the fracture surface, thereby reducing the pressure within the fracture and consequently slowing down the rate of fracture expansion. However, the cross-linker facilitates the participation of free water molecules in the construction of the microscopic grid of the fracturing fluid, thereby reducing the filtration volume and generating greater pressure within the fracture. The promotion of rapid fracture expansion is significantly impacted by the fracture pressure.

Furthermore, it is evident that the utilisation of disparate cross-linking agents will yield a multitude of outcomes and fluctuations in the rheological coefficient of water-based fracturing fluid and the expansion behaviour of coal seam fractures. The regulatory capacity of commercial cross-linking agents in controlling fluid viscosity and fracture expansion behaviour of water-based fracturing fluid is found to be considerably weaker when compared to that of laboratory-synthesised cross-linking agents. This discrepancy can be primarily attributed to the variations in the functional groups present within the molecular structure and the dimensions of the molecules [62]. The absence of a substantial number of polar groups in the commercial cross-linker molecules hinders the formation of additional intermolecular hydrogen bonds and dense microscopic grids with the hydroxyl groups in guar gum. This results in a substantial fluid seepage volume and a diminished pressure increase within the fracture. The fluid viscosity of the water-based fracturing fluid and the expansion capacity of the reservoir fractures exhibit a reduced growth trend upon the addition of commercial cross-linkers [63]. However, the incorporation of synthetic cross-linkers leads to a substantial enhancement of these parameters, even at the same cross-linker content. The presence of additional polar groups in the synthetic cross-linker molecules facilitates enhanced interaction with hydroxyl groups and water molecules present within the guar gum molecules, thereby leading to the formation of increased intramolecular hydrogen bonds and the development of dense microscopic grids. Concurrently, the three-dimensional nanostructure of the synthetic cross-linker will maximise its capacity to interact and form chemical bonds with guar gum and water molecules from all angles. This will significantly reduce the infiltration of free molecules into the reservoir rock through the surface of the coal seam fractures. Furthermore, Figure 3 demonstrates the efficacy of coalbed methane extraction under varying concentrations of cross-linking agents. It is evident from the data presented that the content of cross-linking agent in water-based

fracturing fluid has a direct and significant impact on the sweep coefficient of coal seam fracturing, as well as the amount of coalbed methane extracted (Figure 3c).

3.2. Effects of Fracture Initiation Pressure of Coal Seam Rocks on the Crack Extension

The initiation pressure of coal seam rocks has been demonstrated to impede the propagation behaviour of reservoir fractures, thereby significantly hindering the efficient extraction of coalbed methane. As illustrated in Figure 4, the impact of varying reservoir fracturing pressures on the expansion parameters of coal seam fractures and the subsequent alteration in fluid viscosity is demonstrated. It is evident from the figure that the fluid viscosity of the water-based fracturing fluid in the reservoir fractures will continue to increase with the increase in the fracturing pressure. Conversely, the crack length continues to decrease due to the fracture initiation pressure of the coal seam rock. The fluid viscosity and crack length exhibit a very significant inverse proportional relationship due to the change in fracture initiation pressure.

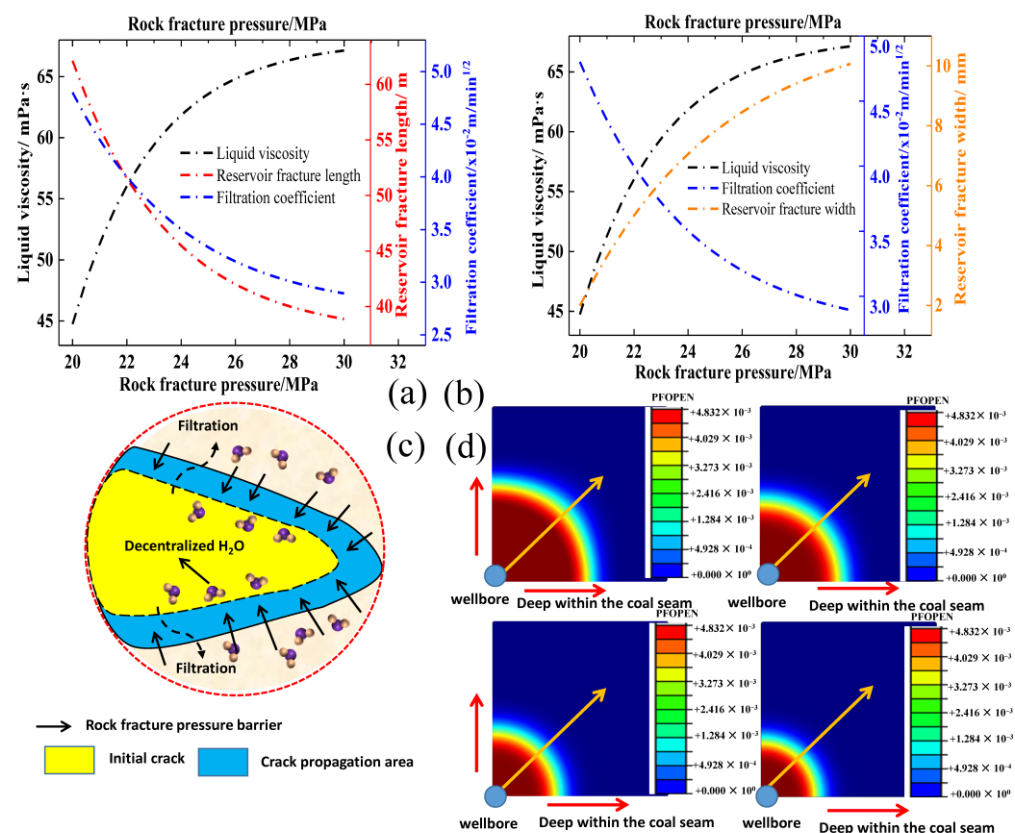


Figure 4. The positive relationship between the rock fracture pressure and fluid viscosity (a,b), and inverse relationship among the rock fracture pressure, coalbed methane extraction efficiency (d) and fracture extension (c) and the filtration coefficient of the water-based fracturing fluid at 0.5 wt% cross-linking agent, 45° of turning angle and 180 °C.

The fluid viscosity increases gradually with the increase in the fracturing pressure of the reservoir rock, mainly because the gradually injected water-based fracturing fluid increases the pressure inside the fracture. The ensuing increase in pressure within the reservoir fracture leads to a gradual increase in the distance between the molecules in the water-based fracturing fluid [64]. This, in turn, directly results in the shortening of the chemical bonds between the molecules that have formed the micro-grid [65]. Concurrently, the enhanced bond energy between the molecules is attributable to the shortened bond length, thereby ensuring the integrity and strength of the micro-grid. Additionally, the free molecules in the water-based fracturing fluid that have not formed intermolecular

hydrogen bonds are continually approaching due to the increase in the internal pressure of the fracture, which helps to form new intermolecular hydrogen bonds. The net effect of these phenomena is a direct increase in the apparent viscosity of the water-based fracturing fluid in the coal seam fractures, accompanied by a gradual increase in the fracture width (Equation (23)).

The elevated fluid viscosity resulting from the fracturing pressure of coal seam rocks may also be associated with fluid loss. The reduced fracturing pressure of the rock may permit the water-based fracturing fluid to rapidly enter the coal seam rock through the surface pores. The low fracture pressure caused by the water-based fracturing fluid after filtration can form a smaller ability for molecules to approach each other. Furthermore, the formation of hydrogen bonds between molecules is forced to weaken due to fluid filtration. It is important to note that although the fluid filtration formed by the smaller coal seam rock fracturing pressure will reduce the fracture pressure, the larger injection rate will not affect the expansion rate of reservoir fractures due to fluid filtration [66]. However, while the larger coal seam fracturing pressure reduces the filtration capacity of the water-based fracturing fluid, it is difficult for the internal pressure of the fracture to break through the larger coal seam fracturing pressure. Consequently, in addition to increasing fluid viscosity, the larger coal seam fracturing pressure will also result in reduced fracture expansion capacity and filtration coefficient.

The fracture initiation pressure of coal seam rocks exhibits a distinct expansion behaviour of reservoir fractures when compared to other factors. An increase in fracture initiation pressure of coal seams results in a reduction in fracture length; however, the width of coal seam fractures continues to expand due to the increase in fluid viscosity. Consequently, the augmentation in fracture initiation pressure of coal seams is unable to achieve the effective expansion of reservoir fractures by water-based fracturing fluids, which has a detrimental effect on the efficient exploitation of coalbed methane.

3.3. Effects of Crack Turning Angle on the Crack Extension

As a pivotal performance indicator of coal seam fractures, the fracture turning angle exerts a substantial influence on fracture propagation and the effective extraction of coalbed methane. As illustrated in Figure 5, the fracture turning angle exerts a substantial influence on the fracture propagation behaviour of coal seams. It is evident from the figure that an increase in fracture turning angle has a substantial effect on the reduction in crack propagation behaviour in coal seam rocks. Conversely, a smaller fracture turning angle will not have a significant hindering effect on the propagation behaviour of coal seam fractures, and a larger fracture length is exhibited at a smaller fracture turning angle [67]. However, a substantial increase in fracture turning angle can lead to a significant reduction in the extension length of coal seam fractures, thereby creating a substantial obstacle to the efficient extraction of coalbed methane.

The inverse proportional relationship between the fracture turning angle and the fracture extension behaviour may be attributed to the adsorption of fluid resistance compounds and the filtration loss of water-based fracturing fluid. When water-based fracturing fluid enters a coal seam fracture at a constant rate with a small turning angle and comes into contact with the fracture surface, it forms a relatively small flow resistance and deflection flow angle. This is not likely to cause a significant obstacle to the flow of water-based fracturing fluid in the coal seam fracture and the pressure in the fracture. Concurrently, the water-based fracturing fluid encounters reduced resistance upon entering the reservoir fracture with a small deflection angle, thereby minimising the probability of the cross-linker and guar in the water-based fracturing fluid coming into contact with the fracture surface [68]. The adsorbed molecules of the cross-linker are reduced on the surface of the reservoir fracture,

which can also reduce the fluid resistance of the water-based fracturing fluid during the flow process. Furthermore, when the water-based fracturing fluid is injected into the reservoir fracture with a small turning angle ($\approx 0^\circ$), the majority of the working fluid will flow into the fracture tip and the depth of the reservoir along the fracture direction. The turning angle of the coal seam fracture that turns to 45° will cause the water-based fracturing fluid injected into the fracture to hit the deflected fracture surface when it flows to the deflected position. Furthermore, it is important to note that not all of the water-based fracturing fluid will continue to flow along the direction of the coal seam fracture after the turn. A study of the effects of the deflection of the fracture on the water-based fracturing fluid shows that 29% ($1 - \cos 45^\circ$) of the water-based fracturing fluid will seep into the coal seam rock due to the deflection of the fracture [57]. This will significantly reduce the internal pressure of the water-based fracturing fluid in the reservoir fracture. Concurrently, the coal seam fracture with a 45° turning angle facilitates the adsorption of the cross-linking agent in the water-based fracturing fluid to the deflected position. This is due to the injection pressure, which enhances the adsorptive capacity of the cross-linking agent on the fracture surface. Consequently, the adsorbed cross-linking agent exerts a greater drag on the water-based fracturing fluid, thereby inducing higher flow resistance. The flow resistance formed by the 45° turning angle has been shown to reduce the impact force of the water-based fracturing fluid to reach the depth of the coal seam and initiate the fracture.

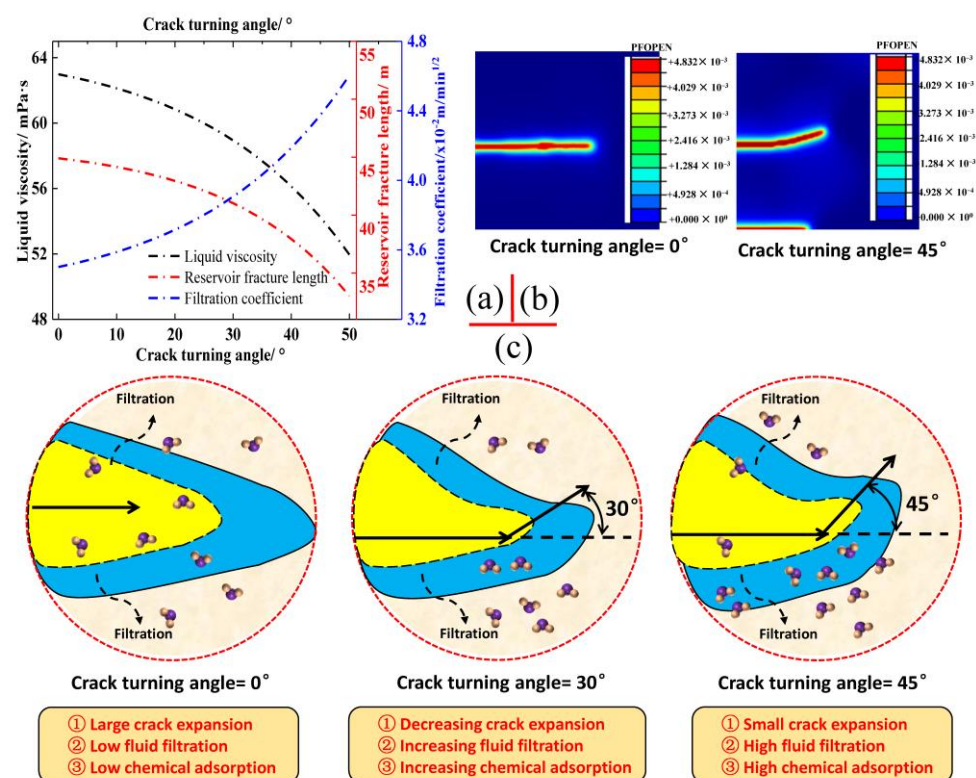


Figure 5. The positive relationship between the crack turning angle and filtration coefficient (a), and inverse relationship among the crack turning angle, fluid viscosity (a) and fracture extension (b,c) at 0.5 wt% cross-linking agent, 20 MPa and 180°C .

A 60° fracture turning angle has been shown to result in 50% of the water-based fracturing fluid injected into the coal seam fractures being pressed into the reservoir rock at the turning moment. This has been demonstrated to significantly reduce the flow of water-based fracturing fluid entering the reservoir fractures. Concurrently, the water-based fracturing fluid that is lost due to substantial filtration will also reduce the internal pressure of the coal seam fractures, thereby posing a considerable challenge to the process

of fracturing through the fracture pressure of the coal seam rock. Consequently, the turning angle will markedly diminish the capacity of water-based fracturing fluid to expand coal seam fractures. Furthermore, an increase in the turning angle will concomitantly result in an escalation in the reservoir loss of water-based fracturing fluid.

3.4. Effects of Coal Seam Temperature on the Crack Extension and Coalbed Methane Mining

The reservoir temperature demonstrates marked variations in different coal seam blocks and coal seam depths, thus representing a significant impediment to the exploration of coalbed methane extraction efficiency. Figure 6 illustrates the alterations in the expansion behaviour of water-based fracturing fluid on coal seam fractures at varying reservoir temperatures, a phenomenon that holds guiding significance for reservoir convergence and the effective recovery of coalbed methane. The reservoir temperature will progressively diminish the fluid viscosity of the water-based fracturing fluid in the coal seam fractures, which will exert a detrimental effect on the expansion of reservoir fractures (Equation (23)). This phenomenon may be associated with the substantial filtration of water-based fracturing fluid at the surface of reservoir fractures, and the analysis and revelation of this filtration process can be facilitated by molecular activity and molecular dynamics.

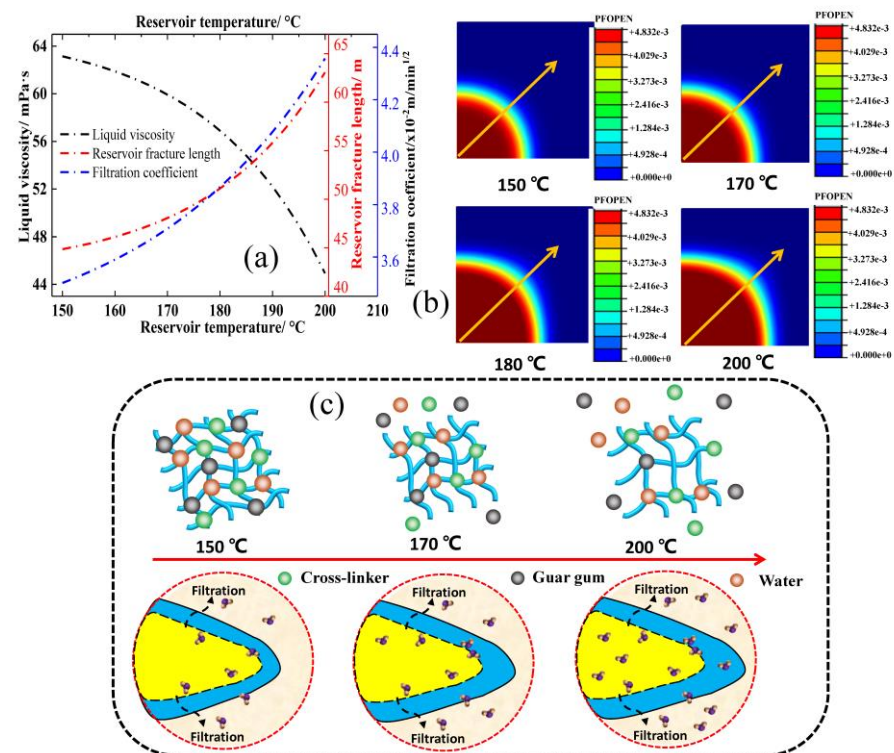


Figure 6. The inverse relationship among the reservoir temperature and fluid viscosity (a), and positive relationship among the reservoir temperature, coalbed methane extraction efficiency (b), and fracture extension (c) at 0.5 wt% cross-linking agent, 20 MPa and 45° of turning angle.

As demonstrated by the Arrhenius equation, the water-based fracturing fluid molecules present within the reservoir fracture exhibit minimal molecular activity under low-temperature conditions. The molecules within the water-based fracturing fluid are unable to become free at low temperatures due to the constraints imposed by intermolecular hydrogen bonds, thereby reducing the probability of the formation of free molecules within the water-based fracturing fluid [56]. Furthermore, at lower reservoir temperatures, the molecules in the water-based fracturing fluid are unable to form more violent irregular motion due to the reduced molecular activity, and the intermolecular hydrogen bonds will not be stretched or sheared at low temperatures. Conversely, at elevated temperatures,

the water-based fracturing fluid will undergo a transition towards a greater prevalence of active molecules, a phenomenon that poses a considerable challenge to the stability of the rheological parameters of the water-based fracturing fluid [64,65]. Increased molecular activity leads to enhanced intermolecular repulsion, which can stretch or break the formed intermolecular hydrogen bonds [66,67]. The fracturing process leads to a reduction in fluid viscosity at the macro level, resulting from the formation of new intermolecular bonds. At the micro level, the presence of free molecules increases due to irregular motion and intermolecular exclusion. It is notable that a greater number of free molecules can infiltrate the coal seam rock through the fracture surface at higher reservoir temperatures, which is not conducive to maintaining the internal pressure of the coal seam fractures [68,69].

Although the low fracture pressure associated with increased reservoir temperature is unfavourable for the expansion of coal seam fractures, the progressively rising reservoir temperature contributes to the volumetric expansion of the water-based fracturing fluid within the fractures [70,71]. Elevated reservoir temperatures enhance molecular activity, thereby increasing the intermolecular repulsive forces [72,73]. This increase in repulsive forces leads to an observable volumetric expansion of the water-based fracturing fluid at the macroscopic scale, exerting a significant positive effect on the internal pressure of reservoir fractures [74,75]. As previously discussed, the continuous increase in internal fracture pressure can quickly surpass the fracture initiation pressure of coal seam rocks, thereby promoting fracture propagation of the coal seam.

As demonstrated in Table 3, a comparison of the parameter differences in fracture propagation behaviour between the present study and the previous literature [76], conducted under analogous reservoir conditions, is provided. This comparison serves to illustrate the enhanced efficacy of the coal seam fracturing model constructed by seepage–stress–damage coupling. Nevertheless, a parallelism in fracture propagation trends is exhibited by both studies, thereby substantiating the reliability and precision of the coal seam fracturing model established in the present study.

Table 3. Differences in fracture extension between the two fracturing models in previous literature [76] and this study at different reservoir temperatures.

Fracturing Model	120 °C	140 °C	160 °C
Preliminary research	6.5 m	7.4 m	9.1 m
This research	42 m	46 m	48 m

As demonstrated in Figure 6, a positive proportional relationship is evident between the extraction efficiency of coalbed methane and the reservoir temperature. This phenomenon can be attributed to two primary factors: (1) As the coal seam temperature increases, the progressively expanding reservoir fractures will interconnect with existing fractures within the reservoir, facilitating the accumulation of coalbed methane and its migration toward the production well. (2) Additionally, the methane molecules adsorbed on the surface of coal seam rocks will undergo continuous desorption with rising reservoir temperature, enabling the desorbed methane to enter the coal seam fractures and flow more efficiently toward the production well.

This study innovatively integrates the seepage–stress–damage coupling model to develop a fracturing model for coal seam fractures, ensuring that fracture propagation behaviour aligns more accurately with the material damage characteristics of coal seam rocks and the initiation of fractures. Additionally, molecular dynamics theory and micro-grid theory of water-based fracturing fluids are incorporated to elucidate the fracture propagation mechanism in coal seams and the adsorption behaviour of coalbed methane. The findings exhibit substantial differences from previous studies on coal seam fracture

propagation [77,78]. Furthermore, kinetic parameters, such as the length and bond energy of chemical bonds, provided insight into the macroscopic variations in coalbed methane adsorption on coal seam rocks and the differences in fluid seepage. These parameters facilitate a more theoretical and microscopic analysis of coalbed methane flow within coal seams and the stress distribution in fractures. The water-based fracturing model developed based on the seepage–stress–damage coupling mechanism not only demonstrates excellent fracture propagation behaviour in coal seams but is also expected to achieve significant fracture expansion in low-permeability shale reservoirs with similar rock properties. The fracturing model constructed in this study is predicated on the assumptions of isotropy and wellbore densification, which are integral to ensuring operational stability. Nevertheless, variations in the physical parameters of actual coal seam rocks, such as permeability, porosity, hardness, and density, may hinder fracture propagation. Additionally, the stability of the coal seam wellbore is identified as a critical factor that requires further consideration and optimisation in future fracturing model developments. The water-sensitive effect of water-based fracturing models in unconventional shale reservoirs is also a key problem that cannot be avoided.

4. Conclusions

In this study, a water-based fracturing fracture extension model based on seepage–stress–damage coupling can provide an effective response strategy for the efficient exploitation of coalbed methane. Simultaneously, the constructed fracture model has the capacity to simulate the geological conditions of low-permeability coal seams, thereby enabling the analysis of the influence of different factors on the fracture propagation behaviour of coal seams. The expansion mechanism of water-based fracturing fluid on coal seam fractures is revealed through the utilisation of molecular theory and rock mechanics analysis of microgrids. The content and type of cross-linking agent have become significant factors in the expansion of coal seam fractures. An increase in cross-linking agent content has been shown to improve the filtration of water-based fracturing fluid, as well as result in a rapid increase in fracture length. Furthermore, coal seam geological conditions, including principal stress and fracture turning angle, have been demonstrated to modify fracture expansion behaviour and coalbed methane extraction efficiency. Furthermore, the reservoir fracturing for coalbed methane extraction has the potential to be transitioned from water-based to CO₂-based fracturing, a shift that could facilitate the attainment of more extensive carbon capture, utilisation and storage (CCUS) and coal seam transformation.

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