

Article

The Impact of Reservoir Parameters and Fluid Properties on Seepage Characteristics and Fracture Morphology Using Water-Based Fracturing Fluid

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Abstract

This study, motivated by the pronounced fluid loss characteristics of water-based fracturing fluids, developed a fluid–solid coupling model to investigate water-based fracturing in geological reservoirs. The model was further employed to analyse the effects of multiple factors on fracture propagation and the seepage capacity of water-based fracturing fluids. Moreover, the underlying mechanisms of fracture propagation and seepage enhancement were elucidated from a microscopic molecular perspective. The results obtained that the high apparent viscosity of water-based fracturing fluids not only enhances the fracturing efficiency of reservoir rocks but also results in a reduced seepage volume (−17 mL) in low-permeability reservoirs. Furthermore, the reservoir porosity (+2.5%) exhibits a clear inverse proportional relationship with fracturing efficiency (−0.9 m), while the seepage volume (+7 mL) of water-based fracturing fluids continues to increase. The strength and quantity of hydrogen bonds between molecules in water-based fracturing fluid, influenced by external factors, directly affect fluid seepage. The seepage behaviour of water-based fracturing fluids in geological reservoirs, together with the influence of reservoir conditions on fracture propagation, provides valuable reference data for rock fracturing and reservoir stimulation. However, the absence of data analysis and microscopic images of microscopic molecular dynamics constitutes a challenging problem that demands attention.

Keywords: enhanced oil recovery; reservoir transformation; petroleum engineering; water-based fracturing; low permeability reservoir



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1. Introduction

The historical progression of global economic development has been predominantly propelled by the utilisation of conventional fossil fuels [1,2]. However, the escalating energy shortage has led to a deceleration in economic growth. Concomitantly, the substantial consumption of conventional energy sources has engendered the emission of considerable quantities of greenhouse gases. These gases are the primary cause of the greenhouse effect and environmental degradation [3]. Consequently, the focus of energy researchers and petroleum engineers has increasingly shifted towards new and unconventional energy sources [4]. It is expected that these alternative energy sources will not only serve as a

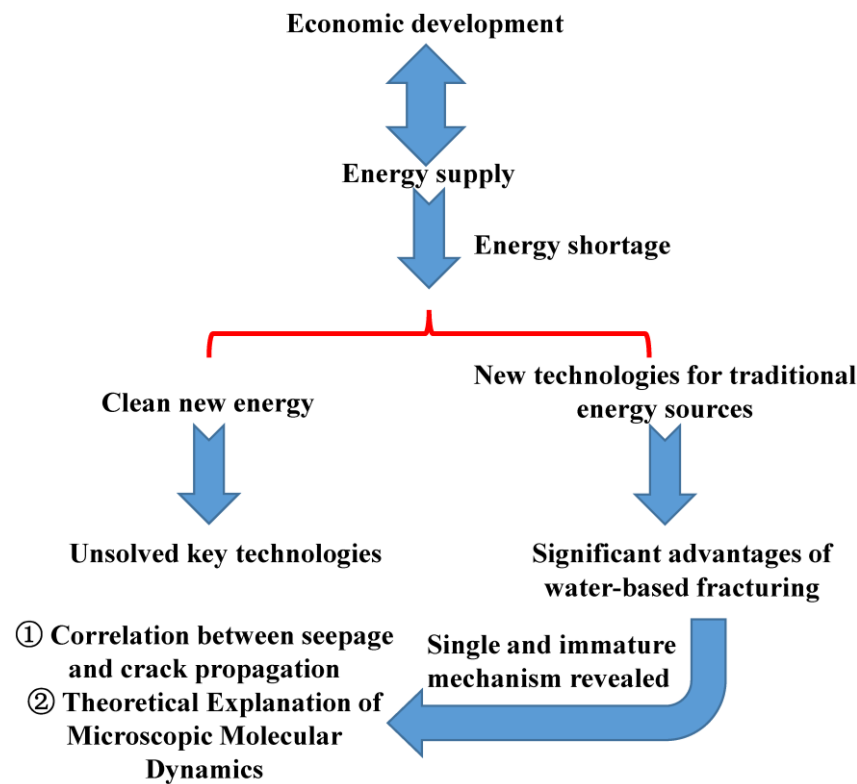
valuable supplement to traditional energy but also contribute to a sustainable and self-reinforcing energy ecosystem [5,6]. However, new and unconventional energy sources are encumbered by a series of disadvantages that preclude their replacement of traditional energy sources, including equipment lag and defects in mining technology. (1) Despite the ecological benefits and the avoidance of the greenhouse effect that have been achieved through the use of new energy sources such as wind power and solar energy, the key to large-scale application of these sources is the stability and reliability of the energy supply [7,8]. However, the low efficiency and the lack of development in energy storage equipment means that the needs of new energy sources during peak energy supply periods cannot be met, which results in significant energy wastage and a reduction in efficiency [9,10]. (2) Although unconventional energy sources, such as shale gas and gas hydrates, exhibit a strong potential to replace traditional energy, the technological lag and mismatch in extraction methods necessitate further exploration by petroleum engineers to optimise the adaptation of conventional extraction techniques for unconventional reservoirs [11,12]. The disadvantages inherent in the utilisation of novel energy applications, consequent to the technical deficit in hardware equipment, are not readily amenable to expeditious resolution [13]. Nevertheless, reservoir transformation measures for conventional energy can be readily enhanced and applied to energy extraction in unconventional reservoirs [14].

As a measure for transforming reservoirs in the context of traditional energy, acid fracturing has demonstrated significant advantages with regard to the expansion of fractures and the enhancement of oil recovery [15,16], and the sweep coefficient of oilfield working fluid in reservoir rocks has exhibited a substantial enhancement effect. Li et al. have demonstrated the remarkable fracture expansion capacity of water-based fracturing in China's oil reservoirs [17], resulting in the formation of 58 m reservoir fractures and the effective accumulation of reservoir oil. Moreover, Khalil et al. utilised hydrochloric acid as the acidising fluid to transform the oil reservoir in the Marcellus block, thereby exploring rock permeability. This resulted in a 39-fold increase in rock permeability and a 13% rise in porosity [18]. Despite the potential of acidizing to enhance EOR (Enhanced Oil Recovery), its numerous drawbacks, including reservoir damage and formation contamination, have led to significant challenges in subsequent reservoir treatment [19,20]. Fracturing technology, as the most widely used method for reservoir transformation, primarily encompasses water-based fracturing, oil-based fracturing, foam fracturing, and CO₂ fracturing [21,22]. Nevertheless, due to inherent limitations, including a restricted application range and suboptimal stability, conventional and unconventional reservoir exploitation is currently impeded by oil-based, foam-based, and CO₂ fracturing techniques [23,24]. In contrast, water-based fracturing fluids are presently suitable for the fracturing conditions of most reservoirs. Nevertheless, the water sensitivity and seepage behaviour of water-based fracturing fluids in low-permeability shale reservoirs hinder fracture propagation, posing a significant challenge to the efficient development of shale energy [25]. Furthermore, elevated temperatures in shale reservoirs have been shown to improve the rheological properties of water-based fracturing fluids, which decreases their thermal stability and reduces filtration control.

All the analysis contents discussed above can be summarised and analysed using Scheme 1.

Thus, this study constructed a flow model of water-based fracturing fluid in shale reservoirs based on the solid–liquid coupling equation in order to analyse the flow behaviour and seepage characteristics of water-based fracturing fluid in low-permeability reservoirs. At the same time, rock fracturing and fracture propagation criteria were used to analyse the expansion behaviour and change trend of reservoir fractures under different reservoir conditions. This helped to achieve energy convergence and efficient exploitation

of unconventional low-permeability reservoirs. Furthermore, molecular dynamics models and hydrogen bond theory have been employed not only to analyse the adsorption and rheological behaviour of water-based fracturing fluid in reservoir rocks, but also to provide a satisfactory explanation for the mechanical changes in reservoir fractures.



Scheme 1. All content related to the introduction section.

2. Materials and Methods

2.1. Reservoir Seepage Model of Water-Based Fracturing Fluid

The reservoir seepage model of water-based fracturing fluid principally addresses the movement of oil and water within reservoir fractures, as well as the seepage of rock matrix. The pertinent models can be categorised into two distinct categories: matrix seepage (Equations (1) and (2)) and fracture seepage (Equations (3) and (4)).

$$\nabla \left(\frac{K_m K_{ro}}{\mu_o B_o} \nabla p_o \right) + \dot{q}_{omw} + \dot{q}_{omf} = \frac{\delta}{\delta_t} \left(\frac{\phi_m s_o}{B_o} \right) \quad (1)$$

$$\nabla \left(\frac{K_m K_{rw}}{\mu_w B_w} \nabla p_w \right) + \dot{q}_{wmw} + \dot{q}_{wmf} = \frac{\delta}{\delta_t} \left(\frac{\phi_m s_w}{B_w} \right) \quad (2)$$

$$\nabla \left(\frac{K_f K_{ro}}{\mu_o B_o} \nabla p_o \right) + \dot{q}_{ofw} - \dot{q}_{omf} = \frac{\delta}{\delta_t} \left(\frac{\phi_f s_o}{B_o} \right) \quad (3)$$

$$\nabla \left(\frac{K_f K_{rw}}{\mu_w B_w} \nabla p_w \right) + \dot{q}_{wfw} - \dot{q}_{wmf} = \frac{\delta}{\delta_t} \left(\frac{\phi_f s_w}{B_w} \right) \quad (4)$$

where K is the permeability of solid rock. k , μ , B and p are the relative permeability, viscosity, volume fraction and pressure of oil and water phases. ϕ is the rock porosity. s is the fluid saturation. $\dot{q}_{omw}$ and $\dot{q}_{wmw}$ are the matrix injection strength of oil and water phases. $\dot{q}_{ofw}$ and $\dot{q}_{wfw}$ are fracture injection strength of oil and water phases. $\dot{q}_{omf}$ and $\dot{q}_{wmf}$ are Matrix-fracture cross-flow strength of oil and water phases. In addition, it is imperative

to close the outer boundary of the seepage model, while the inner boundary is controlled by the well equation.

2.2. Material Damage Criterion for Low Permeability Rocks

Brittle materials, including reservoir rocks, can be characterised using the hyperbolic shape criterion to describe their fracture damage behaviour, as presented in Equation (5) [26].

$$F(\sigma) = \tau^2 - (C - \sigma_n \tan \varphi)^2 + (C - \sigma_R \tan \varphi)^2 \quad (5)$$

where σ_R presented the tensile strength of reservoir rock. C is the cohesion of reservoir rocks, and φ presented the maximum normal stress threshold for reservoir fracture opening. σ_n presented the shear stress. F is the force required for reservoir rock fracture.

The “cohesive fracture” model based on Equation (5) shown in Equation (6) can more effectively explore rock damage and fracture propagation in low-permeability shale reservoirs.

$$F(\sigma, D) = \tau^2 - \sigma_n^2 \tan^2 \theta + 2g(D)\sigma_n\sigma_c - g^2(D)C^2 \quad (6)$$

In which θ is considered as the fracture turning angle inside reservoir rock. σ_c is the hoop strength, and it could be solved by Equation (7). In addition, Figure 1a showed the relationship between θ and σ_R .

$$\sigma_c = \frac{C^2 + \sigma_R^2 \tan^2 \theta}{2\sigma_R} \quad (7)$$

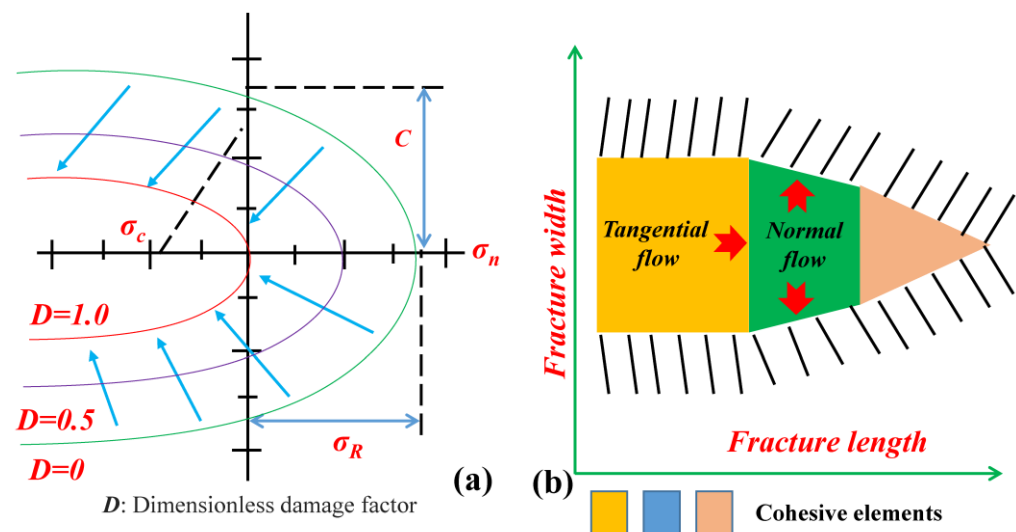


Figure 1. Bond unit failure (a) of brittle materials and reservoir flow (b) of fracturing fluids.

2.3. Fracture Propagation Criteria and of Low Permeability Reservoirs

The Benzeggagh-Kenane fracture criterion is utilised in the damage evolution process of water-based fracturing fluid to reservoir fractures (see Equation (8)) [27].

$$G_n^c + (G_s^c - G_n^c) \left(\frac{G_{sn}}{G_T} \right)^\eta = G^c \quad (8)$$

where G_n , G_s and G_T are considered to be the work done by the traction in the normal direction, the first shear direction and the second shear direction and their conjugate relative displacements, respectively. G^c presented the mixed-mode fracture energy of reservoir fractures, and the critical energy G_n^c , G_s^c and G_T^c required for reservoir rock failure in

different shear directions can be derived by LEFM [28]. G_{Sn} is the actual energy release rate component, and η is the power index.

The flow of water-based fracturing fluid in low-permeability reservoir fractures consists of tangential flow, which drives fracture expansion, and normal flow, which induces fluid leakage into the formation, as illustrated in Figure 1b. The fracturing fluid in the reservoir fracture is an incompressible non-Newtonian fluid, and that the tangential flow is principally governed by the lubrication equation, which is derived from the Poiseuille equation (Equation (9)).

$$q = \frac{d^2}{12\mu} \nabla p \quad (9)$$

where q presented the injection rate of water-based fracturing fluid, μ and ∇p are the viscosity of water-based fracturing fluid and reservoir internal pressure. D is the fracture width.

Concurrently, the normal phase flow adheres to the parameters delineated in Equation (10) [29].

$$\begin{aligned} q_t &= c_t(p_i - p_t) \\ q_b &= c_b(p_i - p_b) \end{aligned} \quad (10)$$

where q_t and q_b are the normal velocity of fracturing fluid on both sides of reservoir fracture, c_t and c_b are considered as the filtration coefficient on the fracture surface. p_i presented the internal pressure of the fracture, p_t and p_b are the pore pressure at the fracture surface.

2.4. Water-Based Fracturing Model for Low Permeability Reservoirs

A two-dimensional water-based fracturing grid model comprising 32,000 CPE4P units was developed, which facilitates the analysis of the fracturing process and seepage behaviour of low-permeability shale reservoirs under varying geological structures and fluid parameters. Furthermore, an isotropic fracturing model is situated at the centre as the injection point for the water-based fracturing fluid, with opposing initial fractures surrounding the wellbore. Furthermore, the sophisticated grid surrounding the wellbore ensures stable model operation and enhances convergence. Figure 2 and Table 1 showed the water-based fracturing model and the characteristic parameters of low-permeability shale reservoirs are demonstrated, respectively. In addition, the boundary conditions and initial conditions of the numerical model are also placed in Table 2, which helps the crack propagation model shown in Figure 2 to be run more accurately.

Table 1. Water-based fracturing parameters for reservoir fracturing models.

Parameter	Value	Parameter	Value
Elastic Modulus, E /GPa	26	Poisson's ratio, ν	0.19
Minimum horizontal principal stress, σ_h /MPa	33	Maximum horizontal principal stress, σ_H /MPa	36
Tensile strength, C /MPa	6.5	Initial pore pressure, P_{ip} /MPa	21
Initial porosity, ϕ /%	7–10	Permeability, K /m ²	5.8×10^{-16}
Leak-off coefficient	2.6×10^{-12}	Total fracturing time, T /min	12

Table 2. Boundary conditions and initial conditions of the numerical model.

Initial Conditions	Value	Boundary Conditions	Value
Initial fracturing length/m	0.3	Injection rate/m ³ /min	16
Initial fracturing width/m	0.01	Far-field pore pressure/MPa	33
Deflection angle of the fracturing/°	45	Pressure on the fracturing surface/MPa	21
Initial pressure of fluid in the fracture/MPa	33	Rock heat transfer coefficient/W/(m·K)	3.1
Initial pressure at injection point/MPa	35	Far-field displacement/m	0

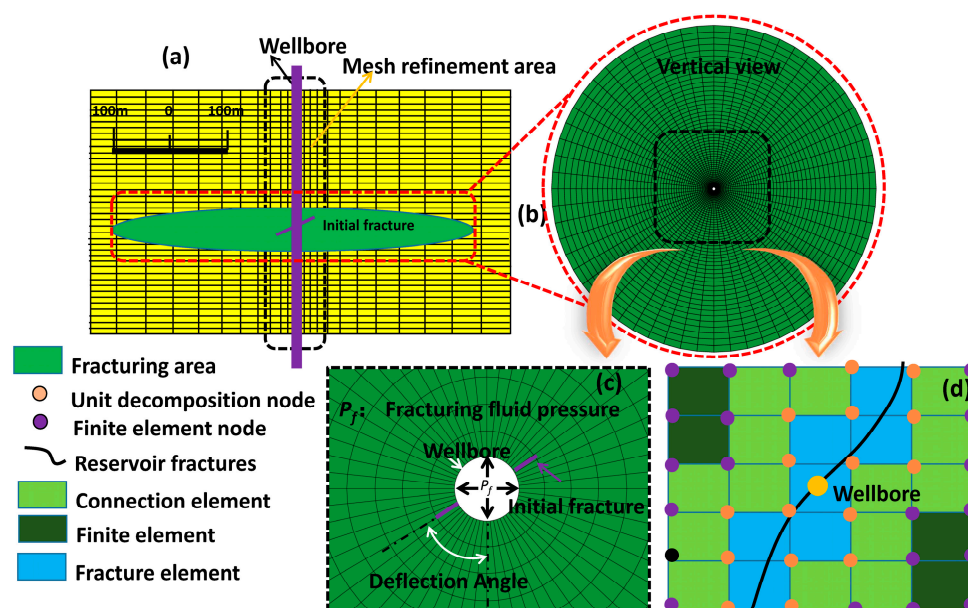


Figure 2. Water-based fracturing model for low-permeability shale reservoirs. (a) Three-dimensional fracturing of injection wells. (b) Top-down model of water-based fracturing. (c) Wellbore mechanics analysis of top-down model. (d) Fracture element classification of crack propagation.

As illustrated in Table 3, the data comparison and feasibility analysis results of the fracturing numerical model constructed in this study are presented alongside those of the numerical models documented in other literature. In accordance with the conditions stipulated in the extant literature, the experimental data presented in this study demonstrated a satisfactory degree of overlap with those reported in the literature, and the numerical model employed in this study exhibited enhanced fracturing performance.

Table 3. Comparative analysis of numerical models and experimental results in the reference [30].

Data Source	100s	200s	300s	400s
Simulation results of this study	17.2	25.4	32.7	36.1
Comparative Data	17.1	25.2	32.4	35.8

2.5. Molecular Dynamics Model

The molecular dynamics model utilises water, guar gum, and a boron-based crosslinker as its fundamental components, with the compass force field employed to optimise the three molecular structures. The Amorphous Cell module constructs an amorphous aqueous solution model of a specific fracturing fluid content, and the Forcite module performs energy-minimising geometry optimisation. In conclusion, the establishment of pertinent data, including chemical bonds, within the optimised water-based fracturing fluid model, results in the subsequent display of the corresponding chemical bond lengths. This method is employed to quantitatively describe the changing trends of chemical bond lengths and bond breakage under different conditions (defined temperature, pressure, and crosslinker content).

3. Results and Discussion

3.1. Effect of Fluid Viscosity on Reservoir Seepage and Fracture Propagation

The viscosity of water-based fracturing fluids significantly influences both fracture propagation and fluid seepage, as illustrated in Figure 3. A strong inverse proportional relationship is observed between fracturing fluid viscosity and reservoir seepage [31,32], whereas the fracture propagation parameter in low-permeability reservoirs increases with

the gradual rise in fluid viscosity. Furthermore, the trends depicted in Figure 3 indicate a clear positive correlation between fracture propagation and fluid seepage, where a lower seepage capacity of the water-based fracturing fluid results in a larger fracture propagation parameter. The relationship between seepage capacity and fracture expansion may be related to the fact that smaller seepage can cause the pressure in the fracture to be quickly accumulated to the minimum fracture initiation pressure, while larger liquid seepage cannot cause the pressure in the fracture to be quickly accumulated to the minimum fracture initiation pressure that causes fracture expansion [33,34]. It is also important to note from Figure 3 that low viscosity fracturing fluid will not cause significant changes in crack expansion and liquid seepage, but high viscosity will promote a rapid increase in crack expansion rate and a decrease in liquid seepage [35].

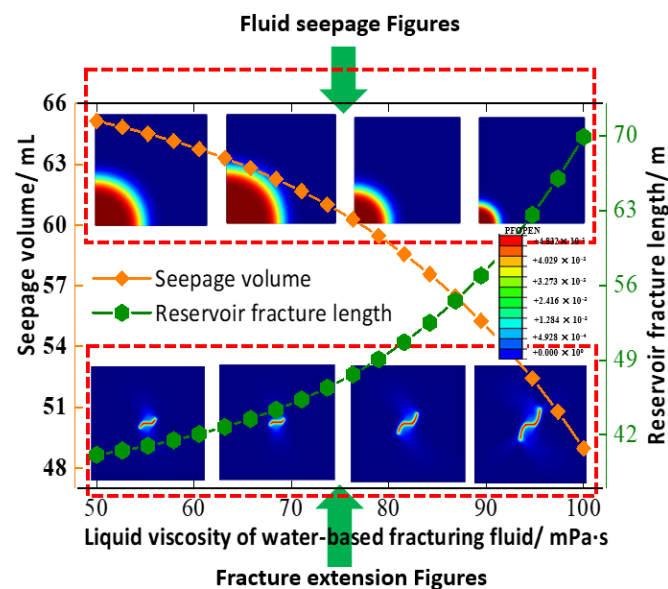


Figure 3. Effect of fluid viscosity on fluid seepage and fracture propagation.

The reduction in seepage of water-based fracturing fluids within reservoir fractures has been identified as a key factor in enhancing fracture propagation, as demonstrated through molecular dynamics simulations and mechanical analysis. At the microscopic level, polar groups in guar gum, cross-linking agents, and water molecules interact to form intermolecular hydrogen bonds, facilitating the cross-linking of molecules within the water-based fracturing fluid and leading to the formation of a microscopic grid structure. This microscopic grid [36] not only enhances the apparent viscosity of the water-based fracturing fluid but also alters its seepage behaviour within reservoir fractures (Figure 4).

The disparities in fluid percolation behaviour under varying fluid viscosities, as previously referenced, may be attributable to the formation of microscopic grids between molecules and alterations in chemical bond lengths [37]. The structured network of water-based fracturing fluid (Figure 4), formed through the interaction of free molecules via polar groups, reduces the number of free water molecules within the fluid. Consequently, only a negligible amount of free water molecules can infiltrate the reservoir rock through the fracture surface [38]. This observation is consistent with the markedly reduced seepage volume under elevated-viscosity conditions, as shown in Figure 4a. Reduced fluid seepage mitigates significant fracturing fluid seepage, thereby contributing to increased pressure within the reservoir fracture and facilitating its expansion (Equation (9)). Furthermore, the lower viscosity of water-based fracturing fluid results in a higher concentration of free molecules due to weaker intermolecular interactions [39], leading to extensive fluid seepage into the reservoir rock. This excessive seepage inhibits reservoir pressure buildup

and slows the fracture propagation rate, whereas higher fluid viscosity exhibits entirely different characteristics. The ability of higher-viscosity fluids to induce rapid fracture propagation primarily stems from their extremely low seepage capacity within dense micro-grid structures, which directly facilitates the rapid buildup of water-based fracturing fluid pressure to the fracture initiation threshold of reservoir fractures [40]. Additionally, the higher micro-grid density associated with increased fluid viscosity enhances resistance to shear forces induced by fluid flow, thereby minimising the generation of free molecules due to shear-induced disruption. In contrast, the weaker micro-grid structure formed under lower fluid viscosity cannot withstand comparable shear forces, which is a key factor contributing to increased fluid seepage and reduced fracture propagation efficiency in low-viscosity conditions [41]. The preceding analysis of fluid viscosity, free molecular concentration, and fracture pressure is corroborated by the intermolecular bond lengths [42] presented in Figure 4b, which provide a clearer explanation of the relationship between fluid seepage and fracture propagation under varying viscosities, as shown in Figure 4a.

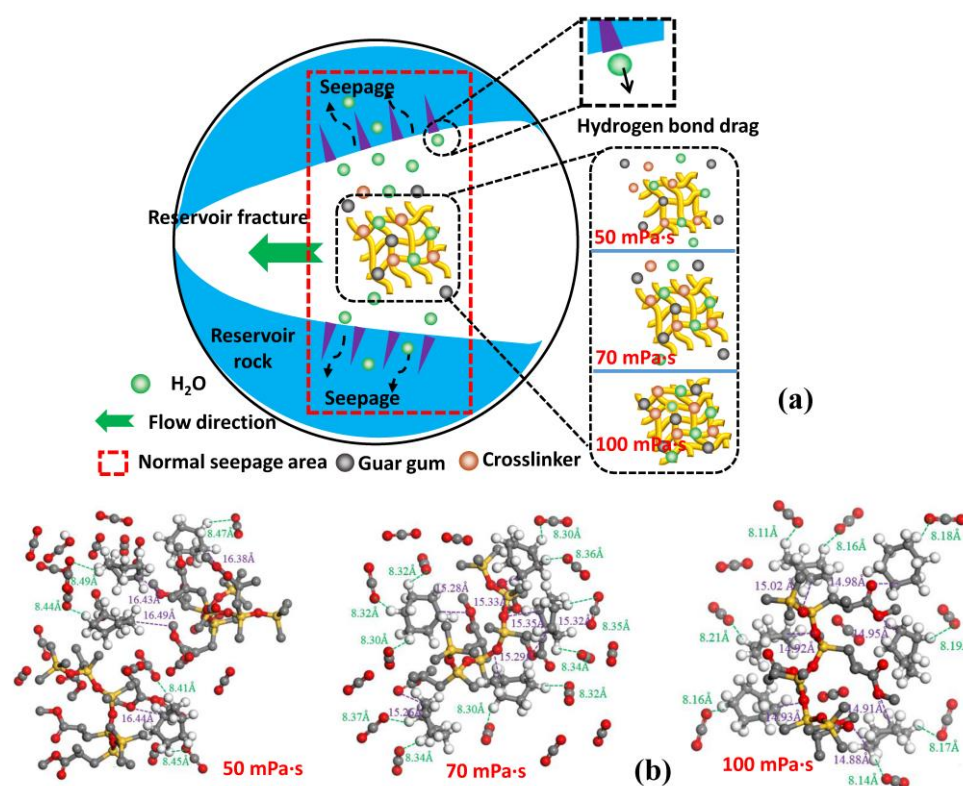


Figure 4. Fluid seepage and micro-grid analysis of different viscosities. (a) Fluid flow in fractures. (b) Changes in intermolecular chemical bonds with fluid viscosity.

3.2. Effect of Reservoir Temperature on Reservoir Seepage and Fracture Propagation

As demonstrated in Figure 5, the effect of reservoir temperature on the flow capacity of water-based fracturing fluid in reservoir fractures is entirely distinct from that of fluid pressure. However, the fracture extension behaviour is analogous to that observed with increasing reservoir temperature and fluid viscosity [43,44]. Alterations in reservoir temperature will result in fluid seepage and fracture expansion exhibiting analogous growth trends, constituting a significant manifestation that is divergent from the influence of fluid viscosity on the aforementioned parameters [45]. The increase in reservoir temperature facilitates the infiltration of water-based fracturing fluid from the surface of reservoir fractures into the surrounding rock, with fluid flow capacity at high temperatures being significantly greater than at low temperatures [46]. Additionally, although a positive correlation between reservoir temperature and fracture propagation is observed, variations

in temperature lead to distinct fracture growth patterns. Lower reservoir temperatures result in reduced fracture propagation capacity, whereas higher temperatures induce an exponential increase in fracture propagation.

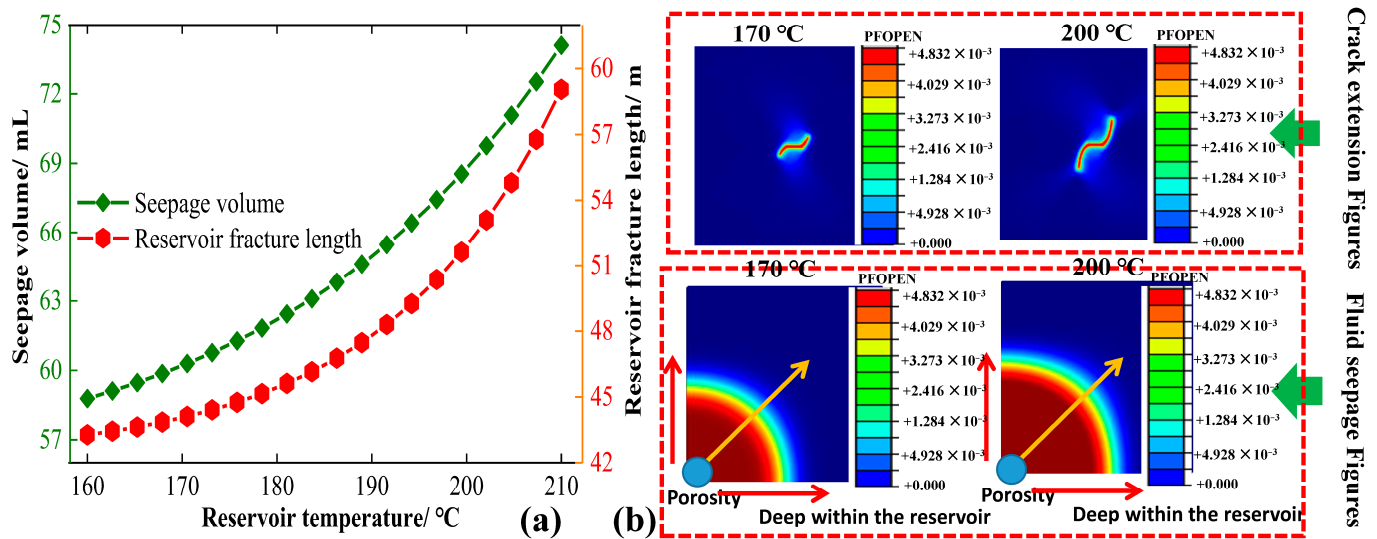


Figure 5. Effect of reservoir temperature on fluid seepage and fracture propagation. (a) Relationship curve between reservoir temperature and seepage volume. (b) Effect of reservoir temperature on fracture propagation.

The Arrhenius equation has been demonstrated to be a useful theoretical framework for understanding the impact of reservoir temperature on the seepage behaviour of water-based fracturing fluid within reservoir fractures [47]. Furthermore, the equation provides a molecular dynamics-based explanation for the mechanism of fracture expansion. It has been shown that lower reservoir temperatures result in the water-based fracturing fluid remaining in reservoir fractures being in a more stable state [48]. This is due to the fact that smaller molecular activity prevents larger irregular motions from forming. The intermolecular hydrogen bonds and microscopic grids formed between molecules will not produce significant extensions or breaks at low reservoir temperatures, thereby reducing the likelihood of microscopic grids becoming thinner at low reservoir temperatures [49,50]. Concurrently, the weaker hydrogen bond stretching or breaking at low reservoir temperatures will also impede the water-based fracturing fluid from forming too many free molecules [51,52], which will cause the water molecules to be dragged by the cross-linking agent and guar gum on a macro scale and unable to seep into the rock through the fracture surface [53,54]. Furthermore, reduced fluid seepage at low reservoir temperatures will result in the majority of water-based fracturing fluid injected into the reservoir fractures being retained. This can lead to more rapid pressure build-up in the reservoir fractures, which in turn can initiate fracture formation and cause rock damage [55,56]. Conversely, higher reservoir temperatures will not only lead to observable fluid seepage behaviour [57], but will also significantly accelerate fracture expansion due to the increasing reservoir temperature. It has been established that elevated reservoir temperatures can substantially augment the movement activity of each molecule in the water-based fracturing fluid. This can result in irregular Brownian motion between molecules. The augmented movement frequency engenders continuous stretching of the hydrogen bonds formed between molecules [58], with the molecules exhibiting greater activity also breaking the molecules to form free molecules. Furthermore, higher reservoir temperatures can increase the repulsive force between molecules of the same polarity, thereby also stretching and breaking the hydrogen bonds between molecules [29,59]. The molecules that are formed at elevated

temperatures lack the pullback of guar gum and cross-linking agents in the water-based fracturing fluid [60,61]. These molecules will rapidly reach the surface pores of the reservoir rock and seep into the rock. Although more fluid seeps into the reservoir rock at higher temperatures, the molecular diffusion and exclusion caused by high temperature also increase the fluid volume of the water-based fracturing fluid [62,63]. The enhanced fluid volume at elevated temperatures can expedite the internal pressure of the reservoir fracture, which is associated with the accelerated expansion of the reservoir fracture. Consequently, while elevated reservoir temperatures can result in water-based fracturing fluid seepage, the concurrent fracture expansion can effectively mitigate the aforementioned defects [64,65].

3.3. Effects of Rock Porosity on Reservoir Seepage and Fracture Propagation

Geological parameters of reservoir rock significantly influence the seepage and filtration capacity of water-based fracturing fluids [66]. Moreover, variations in geological reservoir parameters induce substantial changes in fracture propagation behaviour [67,68]. Figure 6 illustrates the relationship between the initial porosity of the reservoir rock and the seepage and fracture propagation characteristics of water-based fracturing fluids. The seepage volume of water-based fracturing fluid gradually increases with rising rock porosity [69,70]. However, as porosity increases, fracture propagation exhibits a decreasing trend, with distinct fracture growth patterns emerging across different porosity ranges [71,72]. Lower rock porosity not only results in reduced seepage of water-based fracturing fluid but also facilitates the development of larger reservoir fractures, as weaker fluid seepage under low porosity enhances fracture expansion parameters (e.g., fracture length and width) [73,74]. Conversely, at higher rock porosity, an exponential increase in reservoir seepage is observed, inevitably leading to a rapid decline in fracture propagation [75].

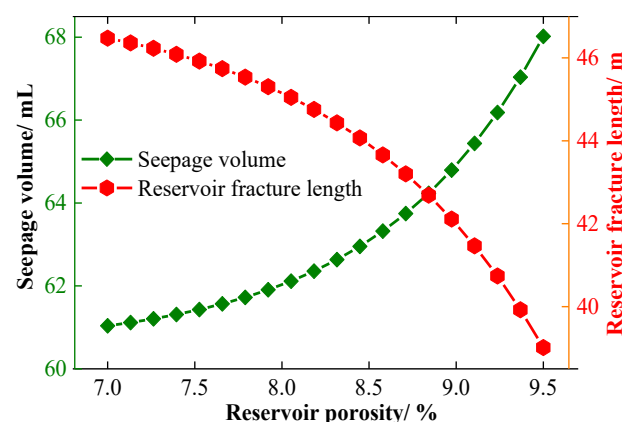


Figure 6. Effect of Reservoir porosity on fluid seepage and fracture propagation.

The seepage of water-based fracturing fluid within the reservoir rock primarily occurs along the fracture surface where normal-phase flow dominates, directly driving the pressurised fluid into the reservoir rock through surface pores [76,77]. When flowing through low-porosity reservoir rock, water-based fracturing fluid within the fracture infiltrates the reservoir pores along the rock surface. The reduction in pore size leads to an instantaneous increase in the shear effect exerted by the fluid [78,79]. Shear-induced free molecules enhance fluid seepage, subsequently reducing pressure within the fracture. The diminished fluid pressure in the reservoir fracture fails to exceed the fracture initiation pressure of the reservoir rock [80,81], thereby decelerating fracture propagation. However, the gel state of cross-linking agents and guar in the water-based fracturing fluid progressively obstructs reservoir pores upon entering low-porosity formations, mitigating excessive fluid seepage. Simultaneously, the blockage of normal pores by the gel forces the fracturing fluid within the reservoir fracture to rapidly reach the fracture initiation pressure of the

reservoir rock [82,83]. The high porosity of reservoir rock facilitates the infiltration of a substantial volume of injected water-based fracturing fluid into the formation through rock pores on the normal surface [84], leading to a significant reduction in fluid pressure within the reservoir fracture [85]. The pressure loss caused by fluid seepage prevents the fracture pressure from reaching the minimum threshold required for rock fracturing, thereby slowing the propagation rate of reservoir fractures [86,87]. Additionally, the gel present in the water-based fracturing fluid fails to accumulate in larger pores, preventing the reduction in fluid seepage that typically results from gel blockage [88,89]. The slower pressure buildup within the reservoir further limits the potential for fracture propagation. Consequently, although the rock porosity may induce gel-related formation damage, the increased fracture propagation contributes to enhanced energy recovery.

3.4. Effects of Reservoir Pressure on Reservoir Seepage and Fracture Propagation

Reservoir pressure is a critical factor influencing the physical and chemical properties of oilfield working fluids and crude oil in geological formations, as it significantly alters the rheological parameters and fracture propagation behaviour of water-based fracturing fluids, as shown in Figure 6. As demonstrated in Figure 7, reservoir pressure plays a crucial role in preventing the infiltration of water-based fracturing fluids into reservoir rocks through the normal surface of reservoir fractures. The figure also illustrates the expansion capacity of reservoir fractures as reservoir pressure gradually increases. However, it is essential to note that low reservoir pressure results in a relatively weaker reduction in fluid seepage. In contrast, higher reservoir pressure induces a more pronounced exponential decline in fluid seepage. The distinct growth trends observed under varying reservoir pressures are reflected in the behaviour of reservoir fractures, which can be primarily attributed to the effect of reservoir pressure on the hydrogen bonding between water-based fracturing fluid molecules and the pressure within fractures [90,91].

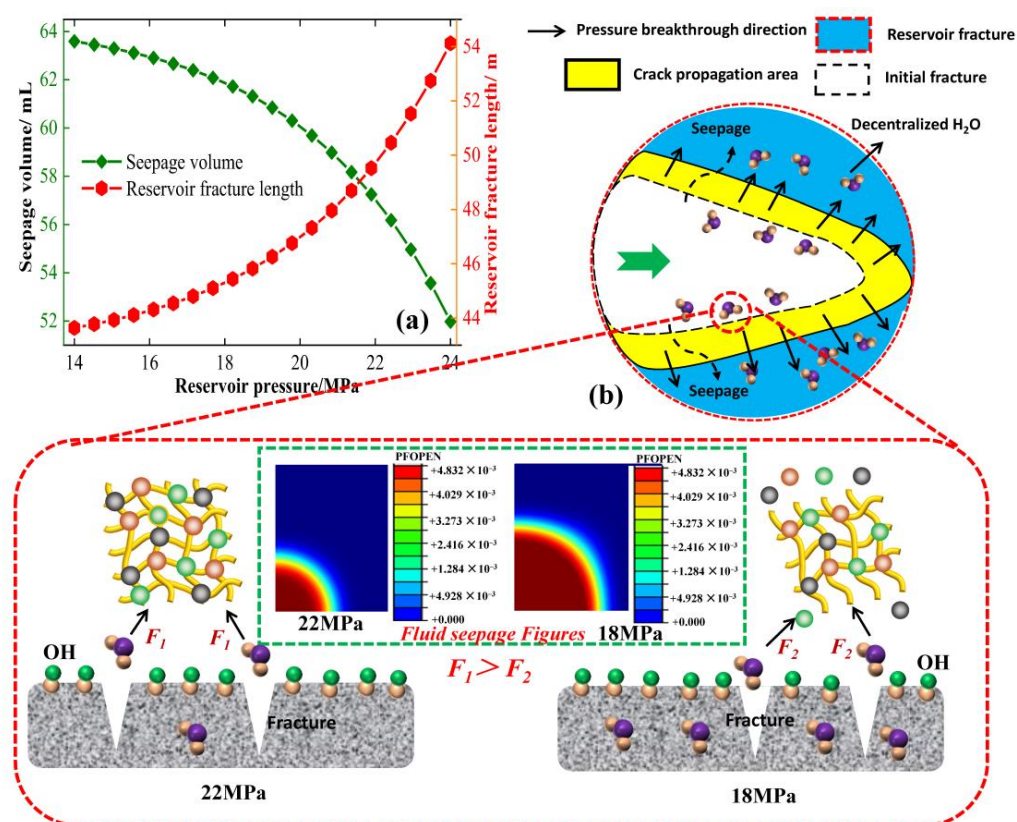


Figure 7. Effect of reservoir pressure on fluid flow (a) and fracture propagation (b).

Lower reservoir pressure alters the morphology and quantity of hydrogen bonds between guar gum and water molecules in water-based fracturing fluid, exerting a decisive influence on its rheological properties and seepage behaviour [92,93]. At low reservoir pressure, a limited number of free molecules at a distance form intermolecular hydrogen bonds due to the attraction of polar groups, which slightly constrains a small fraction of free water molecules interconnected by microscopic grids and intermolecular hydrogen bonds [94,95]. The inherently low concentration of free molecules in the water-based fracturing fluid is further restricted by the drag effect of guar gum, preventing their infiltration into the reservoir rock through surface pores within the fracture [96,97]. However, the marginal enhancement in fluid seepage capacity results in only a slight improvement in fracture propagation [98,99]. Achieving optimal fracture propagation requires reduced fluid seepage under elevated reservoir pressure [100,101]. Elevated reservoir pressure gradually reduces the bond length of existing intermolecular hydrogen bonds, thereby increasing their bond energy within the water-based fracturing fluid [102,103]. Simultaneously, free molecules that remain unbonded under low reservoir pressure form new hydrogen bonds under high-pressure conditions [104,105], significantly reducing the number of free molecules in the fracturing fluid [106,107].

The continuous shortening of hydrogen bonds, along with the formation of new intermolecular hydrogen bonds, enhances the microscopic grid density within the water-based fracturing fluid [108,109]. Consequently, water molecules experience stronger drag forces from guar gum molecules, preventing their infiltration into rock pores along the normal direction of the fracture [110,111]. Reduced fluid seepage facilitates the rapid buildup of fracturing fluid pressure to the rock fracture initiation threshold, leading to an exponential increase in fracture propagation [112,113], as illustrated in the high-reservoir-pressure range of Figure 6. Thus, the influence of reservoir pressure on the seepage of water-based fracturing fluid in fractures and fracture propagation is primarily attributed to the morphological changes in microscopic hydrogen bonds [114,115]. The increased bond energy of intermolecular hydrogen bonds and the higher microscopic grid density under elevated pressure effectively promote the retention of water-based fracturing fluid within reservoir fractures [116–118], thereby achieving efficient pressure maintenance [119,120].

4. Conclusions

The numerical model developed in this study for evaluating the performance of water-based fracturing fluids in reservoir fractures enables a comprehensive and accurate assessment of their limitations, particularly the weak fracture propagation and severe seepage observed during reservoir stimulation. The findings further demonstrate that incorporating a cross-linking agent to enhance fluid viscosity can effectively mitigate excessive seepage and improve fracture propagation, while reservoir conditions (e.g., temperature and pressure) also exert significant influence on the effectiveness of water-based fracturing fluids in promoting fracture growth. Moreover, the identified relationships among fluid viscosity, fluid seepage, and fracture propagation under varying conditions provide new insights for elucidating the underlying mechanisms and for identifying potential improvement strategies. Finally, the three-dimensional micro-grid model constructed in this study has been validated as applicable for analysing the coupled effects of water-based fracturing fluids on fracture pressure and propagation under diverse reservoir conditions. The numerical model constructed in this study only considers simple fracture propagation in homogeneous rocks, which is inherently inadequate for fracture propagation in complex fracture networks within heterogeneous reservoirs. It is inevitable that future research will concentrate on the fracture propagation behaviour in complex fracture net-

works based on realistic geological parameters. This will make numerical models more practical for application.

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Nomenclature

Physical Parameters	Alphabet Symbols	Physical Parameters	Alphabet Symbols
relative permeability	k	rock porosity	ϕ
fluid viscosity	μ	matrix injection strength of oil	$\dot{q}_{omw}$
volume fraction	B	the matrix injection strength of water	$\dot{q}_{wmw}$
pressure	p	fracture injection strength of oil	$\dot{q}_{ofw}$
Matrix-fracture cross-flow strength of oil	$\dot{q}_{omf}$	fracture injection strength of water	$\dot{q}_{wfw}$
Matrix-fracture cross-flow strength of water	$\dot{q}_{wmf}$	tensile strength of reservoir rock	σ_R
maximum normal stress threshold for reservoir fracture opening	φ	cohesion of reservoir rocks	C
force required for reservoir rock fracture	F	shear stress	σ_n
fracture turning angle	θ	hoop strength	σ_c
traction in the normal direction	G_n	traction in first shear direction	G_s
the second shear direction	G_T	mixed-mode fracture energy	G^c
actual energy release rate component	G_{Sn}	power index	η
injection rate	q	reservoir internal pressure	∇p
fracture width	D	normal velocity of first side	q_b
normal velocity of second side	q_t	filtration coefficient of first side	c_t
filtration coefficient of second side	c_b	internal pressure	p_i
pore pressure of first side	p_t	pore pressure of second side	p_b

References

1. Ma, X.; Sun, Y.; Liu, B.; Guo, W.; Jia, R.; Li, B.; Li, S. Numerical study of depressurization and hot water injection for gas hydrate production in China's first offshore test site. *J. Nat. Gas Sci. Eng.* **2020**, *83*, 103530. [[CrossRef](#)]
2. Kreipl, M.P.; Kreipl, A.T. Hydraulic fracturing fluids and their environmental impact: Then, today, and tomorrow. *Environ. Earth Sci.* **2017**, *76*, 160. [[CrossRef](#)]
3. Liu, Y.F.; Zhou, L.; Wan, X.C.; Tang, Y.F.; Liu, Q.; Li, W.; Liao, J.B. Synthesis and characterization of a temperature sensitive microcapsule gelling agent for high-temperature acid release. *ACS Omega* **2024**, *9*, 20849–20858. [[CrossRef](#)] [[PubMed](#)]
4. Emblemavåg, J. Wind energy is not sustainable when balanced by fossil energy. *Appl. Energy* **2022**, *305*, 117748. [[CrossRef](#)]
5. Li, Q.; Li, Q.; Wu, J.; Li, X.; Li, H.; Cheng, Y. Wellhead stability during development process of hydrate reservoir in the Northern South China Sea: Evolution and mechanism. *Processes* **2024**, *13*, 40. [[CrossRef](#)]
6. Wang, F.; Li, Q.; Xiao, Z.; Jiang, B.; Ren, J.; Jin, Z.; Li, X. Conversion of rice husk biomass into electrocatalyst for oxygen reduction reaction in Zn-air battery: Effect of self-doped Si on performance. *J. Colloid Interface Sci.* **2022**, *606*, 1014–1023. [[CrossRef](#)]
7. Li, Q.; Li, Q.; Wang, F.; Wu, J.; Wang, Y. The carrying behavior of water-based fracturing fluid in shale reservoir fractures and molecular dynamics of sand-carrying mechanism. *Processes* **2024**, *12*, 2051. [[CrossRef](#)]

8. Lei, Q.; Weng, D.; Liu, H.; Guan, B.; Deng, Q.; Yan, X.; Ma, Z. Progress and development directions of shale oil reservoir stimulation technology of China National Petroleum Corporation. *Pet. Explor. Dev.* **2021**, *48*, 1198–1207. [\[CrossRef\]](#)
9. Amir, M.; Deshmukh, R.G.; Khalid, H.M.; Said, Z.; Raza, A.; Muyeen, S.M.; Sopian, K. Energy storage technologies: An integrated survey of developments, global economical/environmental effects, optimal scheduling model, and sustainable adaption policies. *J. Energy Storage* **2023**, *72*, 108694. [\[CrossRef\]](#)
10. Khan, M.K.; Raza, M.; Shahbaz, M.; Farooq, U.; Akram, M.U. Recent advancement in energy storage technologies and their applications. *J. Energy Storage* **2024**, *92*, 112112. [\[CrossRef\]](#)
11. Seyyedattar, M.; Zendehboudi, S.; Butt, S. Technical and non-technical challenges of development of offshore petroleum reservoirs: Characterization and production. *Nat. Resour. Res.* **2020**, *29*, 2147–2189. [\[CrossRef\]](#)
12. Li, Q.; Liu, J.; Wang, S.; Guo, Y.; Han, X.; Li, Q.; Cheng, Y.; Dong, Z.; Li, X.; Zhang, X. Numerical insights into factors affecting collapse behavior of horizontal wellbore in clayey silt hydrate-bearing sediments and the accompanying control strategy. *Ocean Eng.* **2024**, *297*, 117029. [\[CrossRef\]](#)
13. Du, S.-H.; Shi, Y.-M. Concise extraction and characterization of the pore-throat network in unconventional hydrocarbon reservoirs: A new perspective. *Pet. Sci.* **2024**, *21*, 1474–1487. [\[CrossRef\]](#)
14. Liew, M.S.; Danyaro, K.U.; Zawawi, N.A.W.A. A comprehensive guide to different fracturing technologies: A review. *Energies* **2020**, *13*, 3326. [\[CrossRef\]](#)
15. Guo, J.; Gou, B.; Qin, N.; Zhao, J.; Wu, L.; Wang, K.; Ren, J. An innovative concept on deep carbonate reservoir stimulation: Three-dimensional acid fracturing technology. *Nat. Gas Ind. B* **2020**, *7*, 484–497. [\[CrossRef\]](#)
16. Shang, J.; Dong, Z.; Tan, W.; Zhang, Y.; Liang, T.; Xing, L.; Wang, Z. A review of fracturing and enhanced recovery integration working fluids in tight reservoirs. *Processes* **2024**, *12*, 1241. [\[CrossRef\]](#)
17. Li, Q.; Li, Q.; Cao, H.; Wu, J.; Wang, F.; Wang, Y. The crack Propagation Behaviour of CO₂ Fracturing Fluid in Unconventional Low Permeability Reservoirs: Factor Analysis and Mechanism Revelation. *Processes* **2025**, *13*, 159. [\[CrossRef\]](#)
18. Khalil, R.; Emadi, H.; Altawati, F. Investigating the effect of matrix acidizing injection pressure on carbonate-rich Marcellus shale core samples: An experimental study. *J. Pet. Explor. Prod.* **2021**, *11*, 725–734. [\[CrossRef\]](#)
19. Yujie, B.; Bin, H.; Che, Z.; Xuenan, X.; Weibo, L.; Zhe, W.; Ning, Z.; Dan, L. Mechanism of enhanced oil recovery by nanoparticles extracted from flowback fluids of acidizing oil wells. *Colloids Surf. A Physicochem. Eng. Asp.* **2024**, *690*, 133782. [\[CrossRef\]](#)
20. da Silva, D.C.; da Silva, N.P.D.; Lourenço, M.C.d.M.; Schwalbert, M.P.; Neto, A.d.O.W.; Rodrigues, M.A.F. Evaluation of carbonate rock acidizing under different reservoir conditions and damage scenarios: A systematic review. *Carbonates Evaporites* **2024**, *39*, 113. [\[CrossRef\]](#)
21. Li, Q.; Wang, Y.; Wang, X.; Yu, H.; Li, Q.; Wang, F.; Bai, H.; Kobina, F. An application of thickener to increase viscosity of liquid CO₂ and the assessment of the reservoir geological damage and CO₂ utilization. *Energy Sources Part A Recovery Util. Environ. Eff.* **2019**, *41*, 368–377.
22. Ranjith, P.G.; Zhang, C.P.; Zhang, Z.Y. Experimental study of fracturing behaviour in ultralow permeability formations: A comparison between CO₂ and water fracturing. *Eng. Fract. Mech.* **2019**, *217*, 106541. [\[CrossRef\]](#)
23. Maleki, M.; Mehrjoo, H.; Kazemzadeh, Y.; Mohammadinia, F.; Ranjbar, A. Green innovation in enhanced oil recovery: Pioneering sustainable solution for a cleaner future. *Environ. Earth Sci.* **2025**, *84*, 60. [\[CrossRef\]](#)
24. Zhao, J.; Wu, T.; Pu, W.; Daijun, D.; Chen, Q.; Chen, B.; Li, J.; Huang, Y. Application status and research progress of CO₂ fracturing fluid in petroleum engineering: A brief review. *Petroleum* **2024**, *10*, 1–10. [\[CrossRef\]](#)
25. Wanniarachchi, W.A.M.; Ranjith, P.G.; Perera, M.S.A.; Lashin, A.; Al Arifi, N.; Li, J.C. Current opinions on foam-based hydro-fracturing in deep geological reservoirs. *Geomech. Geophys. Geo-Energy Geo-Resour.* **2015**, *1*, 121–134. [\[CrossRef\]](#)
26. Pouya, A.; Yazdi, P.B. A damage-plasticity model for cohesive fractures. *Int. J. Rock Mech. Min. Sci.* **2015**, *73*, 194–202. [\[CrossRef\]](#)
27. Benzeggagh, M.L.; Kenane, M. Measurement of mixed-mode delamination fracture toughness of unidirectional glass/epoxy composites with mixed-mode bending apparatus. *Compos. Sci. Technol.* **1996**, *56*, 439–449. [\[CrossRef\]](#)
28. Kanninen, M.F. Applications of dynamic fracture mechanics for the prediction of fracture arrest in engineering structures. *Int. J. Fract.* **1985**, *27*, 299–312. [\[CrossRef\]](#)
29. Gillemot, L.F. Criterion of fracture initiation and spreading. *Eng. Fract. Mech.* **1976**, *8*, 239–253. [\[CrossRef\]](#)
30. Li, Q.; Wang, Y.; Owusu, A.B. A modified Ester-branched thickener for rheology and wettability during CO₂ fracturing for improved fracturing property. *Environ. Sci. Pollut. Res.* **2019**, *26*, 20787–20797. [\[CrossRef\]](#)
31. Wang, G.; Wang, S.; Liu, Y.; Huang, Q.; Li, S.; Xie, S.; Zheng, J.; Fan, J. Influences of clean fracturing fluid viscosity and horizontal in-situ stress difference on hydraulic fracture propagation and morphology in coal seam. *Int. J. Coal Sci. Technol.* **2024**, *11*, 38. [\[CrossRef\]](#)
32. Li, Q.; Li, Q.; Wu, J.; He, K.; Xia, Y.; Liu, J.; Wang, F.; Cheng, Y. Wellhead Stability During Development Process of Hydrate Reservoir in the Northern South China Sea: Sensitivity Analysis. *Processes* **2025**, *13*, 1630. [\[CrossRef\]](#)
33. Shi, Z.; Yao, Q.; Wu, C.; Xu, Y.; Wang, F.; Wang, W.; Sun, J. Interaction between Groundwater and Rock Fractures under Stress and Seepage Based on Extractive Water Resource Utilisation. *Processes* **2023**, *11*, 3380. [\[CrossRef\]](#)

34. Liu, X.; Zhang, J.; Zhou, X.; Liu, Y.; Wang, Y.; Luo, X. Damage-seepage evolution mechanism of fractured rock masses considering the influence of lateral stress on fracture deformation under loading and unloading process. *Rock Mech. Rock Eng.* **2024**, *57*, 10973–10999. [\[CrossRef\]](#)
35. Li, L.; Hao, Y.; Lv, Y.; Wang, C.; Yao, C.; Zhao, Q.; Xiao, P. Experimental investigation on low-velocity seepage characteristics and influencing factors in a shale oil reservoir. *J. Pet. Sci. Eng.* **2020**, *195*, 107732. [\[CrossRef\]](#)
36. Li, Q.; Wang, F.; Wang, Y.; Zhang, J.; Yu, X.; Zhao, M.; Zhou, C.; Forson, K.; Shi, S.; Zhao, Y.; et al. Influence of organoboron crosslinker and reservoir characteristics on filtration and reservoir residual of guar gum fracturing fluid in low-permeability shale gas reservoirs. *Environ. Sci. Pollut. Res.* **2022**, *29*, 82975–82985. [\[CrossRef\]](#)
37. Gong, X.; Mu, L.; Liu, L. Performance Optimisation of Low—Damage Foam Fracturing Fluid System in Unconventional Reservoirs. *Int. J. Chem. Eng.* **2025**, *2025*, 6519044. [\[CrossRef\]](#)
38. Liu, W.; Yang, Y.; Qiao, C.; Liu, C.; Lian, B.; Yuan, Q. Progress of seepage law and development technologies for shale condensate gas reservoirs. *Energies* **2023**, *16*, 2446. [\[CrossRef\]](#)
39. Song, H.; Liu, J. Effects of Modified Cross-Linkers on the Rheology of Water-Based Fracturing Fluids and Reservoir Water Environment. *Processes* **2024**, *12*, 2896. [\[CrossRef\]](#)
40. Gao, M.; Liu, H.; Hu, X.; Wang, Y.; Wang, D.; Qiao, H.; Liu, C.; Yu, W. Shale Gas Three-Dimensional Development Adjustment Workflow Based on Dynamic Changes of Geostress and Artificial Intelligence Algorithm to Achieve Efficient Shale Gas Extraction. In Proceedings of the SPE EOR Conference at Oil and Gas West Asia (SPE 2025), Muscat, Oman, 12–14 May 2025. [\[CrossRef\]](#)
41. Zhang, L.; Wang, H.; Cai, J.; Zhang, S. Application of micro-Seismic monitoring in post-fracturing evaluation of shale gas: A case study of well X from Puguang area, China. *Processes* **2023**, *11*, 1863. [\[CrossRef\]](#)
42. Mousavi, N.; Kothapalli, G.; Habibi, D.; Khiadani, M.; Das, C.K. An improved mathematical model for a pumped hydro storage system considering electrical, mechanical, and hydraulic losses. *Appl. Energy* **2019**, *247*, 228–236. [\[CrossRef\]](#)
43. Li, Q.; Li, Q.; Wang, F.; Wu, J.; Wang, Y.; Jin, J. Effects of Geological and Fluid Characteristics on the Injection Filtration of Hydraulic Fracturing Fluid in the Wellbores of Shale Reservoirs: Numerical Analysis and Mechanism Determination. *Processes* **2025**, *13*, 1747. [\[CrossRef\]](#)
44. Matovu, S.; Al Shafloot, T.; Raza, A.; Mahmoud, M.A.; Hassan, A.; Alarifi, S.; Abu-Mahfouz, I.S. A Novel Approach to Stimulating Tight Reservoirs Using Cyclic Thermochemical Fluids. *Energy Fuels* **2025**, *39*, 14158–14172. [\[CrossRef\]](#)
45. Cai, J.; Yang, J.; Huang, Z.; Xu, S.; Zhang, L.; Wang, H. Quantitative Evaluation of Residual Acid Invasion and Flowback in Fractured-Vuggy Carbonate Reservoirs Using Microfluidics. *Energies* **2025**, *18*, 1162. [\[CrossRef\]](#)
46. Ao, F.; Qingchao, L.; Qiang, L.; Jingjuan, W.; Fuling, W.; Chuanliang, Y. Numerical Simulation Investigation of Fracture Propagation Behavior Patterns and Sensitivity Factors of Oil Shale Reservoirs in the Xunyi Region Considering the Influence of Natural Fracture. *Geofluids* **2025**, *2025*, 2762142. [\[CrossRef\]](#)
47. Li, Q.; Wang, F.; Wang, Y.; Bai, B.; Zhang, J.; Lili, C.; Sun, Q.; Wang, Y.; Forson, K. Adsorption behavior and mechanism analysis of siloxane thickener for CO₂ fracturing fluid on shallow shale soil. *J. Mol. Liq.* **2023**, *376*, 121394. [\[CrossRef\]](#)
48. Zhang, C.P.; Ranjith, P.G.; Perera, M.S.A.; Li, X.; Zhao, J. Simulation of flow behaviour through fractured unconventional gas reservoirs considering the formation damage caused by water-based fracturing fluids. *J. Nat. Gas Sci. Eng.* **2018**, *57*, 100–121. [\[CrossRef\]](#)
49. Liu, Y.; Pei, X.; Yang, F.; Zhong, J.; Dai, L.; Wang, C.; Zhou, T.; Li, Y.; Xiao, S. Molecular Simulation Study of Gas–Water Adsorption Behavior and Mobility Evaluation in Ultra-Deep, High-Pressure Fractured Tight Sandstone Reservoirs. *Energies* **2025**, *18*, 2175. [\[CrossRef\]](#)
50. Qian, T.; Li, J.; Min, X.; Fan, B. Integration of pore confinement and hydrogen-bond influence on the crystallization behavior of C18 PCMs in mesoporous silica for form-stable phase change materials. *ACS Sustain. Chem. Eng.* **2018**, *6*, 897–908. [\[CrossRef\]](#)
51. Liu, G.; Xie, S.; Tian, W.; Wang, J.; Li, S.; Wang, Y.; Yang, D. Effect of pore-throat structure on gas-water seepage behaviour in a tight sandstone gas reservoir. *Fuel* **2022**, *310*, 121901. [\[CrossRef\]](#)
52. Wang, F.; Kobina, F. The influence of geological factors and transmission fluids on the exploitation of reservoir geothermal resources: Factor discussion and mechanism analysis. *Reserv. Sci.* **2025**, *1*, 3–18. [\[CrossRef\]](#)
53. Zeng, L.; Hosseini, M.; Keshavarz, A.; Iglauder, S.; Lu, Y.; Xie, Q. Hydrogen wettability in carbonate reservoirs: Implication for underground hydrogen storage from geochemical perspective. *Int. J. Hydrogen Energy* **2022**, *47*, 25357–25366. [\[CrossRef\]](#)
54. Tao, X.; Zheng, Z.; Yu, H.; Liu, H.; Li, Y.; Zhang, J.; Liu, J.; Zheng, L. Internal blocking and bonding to strengthen the mechanical properties and prevent collapse and leakage of fragmented coalbed methane (CBM) reservoirs by cohesive drilling fluids. *Geoenergy Sci. Eng.* **2024**, *241*, 213136. [\[CrossRef\]](#)
55. Li, Q. Reservoir Science: A Multi-Coupling Communication Platform to Promote Energy Transformation, Climate Change and Environmental Protection. *Reserv. Sci.* **2025**, *1*, 1–2. [\[CrossRef\]](#)
56. Nikraves, M.; Aminzadeh, F. Past, present and future intelligent reservoir characterization trends. *J. Pet. Sci. Eng.* **2001**, *31*, 67–79. [\[CrossRef\]](#)
57. Wu, J.; Ansari, U. From CO₂ Sequestration to Hydrogen Storage: Further Utilization of Depleted Gas Reservoirs. *Reserv. Sci.* **2025**, *1*, 19–35. [\[CrossRef\]](#)

58. Huang, Q.; Liu, S.; Wang, G.; Cheng, W. Evaluating the changes of sorption and diffusion behaviors of Illinois coal with various water-based fracturing fluid treatments. *Fuel* **2021**, *283*, 118884. [\[CrossRef\]](#)
59. Li, Q.; Wang, Y.; Wang, F.; Ning, X.; Chuanbao, Z.; Zhang, J.; Zhang, C. Factor analysis and mechanism disclosure of supercritical CO₂ filtration behavior in tight shale reservoirs. *Environ. Sci. Pollut. R* **2022**, *29*, 17682–17694. [\[CrossRef\]](#)
60. Al-Hajri, S.; Negash, B.M.; Rahman, M.M.; Haroun, M.; Al-Shami, T.M. Perspective Review of polymers as additives in water-based fracturing fluids. *ACS Omega* **2022**, *7*, 7431–7443. [\[CrossRef\]](#)
61. Tang, H.; Tang, H.; He, J.; Zhao, F.; Zhang, L.; Liao, J.; Wang, Q.; Yuan, X. Damage mechanism of water-based fracturing fluid to tight sandstone gas reservoirs: Improvement of The Evaluation Measurement for Properties of Water-based Fracturing Fluid: SY/T 5107-2016. *Nat. Gas Ind. B* **2021**, *8*, 163–172. [\[CrossRef\]](#)
62. Zhang, Y.; Gu, Y.; Sun, Q.; Rui, F.; Ge, Z.; Jia, H. Influence of microwave irradiation and water-based cooling on the fracturing behavior and failure mode transition of CSTBD granite. *Eng. Fract. Mech.* **2024**, *296*, 109832. [\[CrossRef\]](#)
63. Li, Q.; Wu, J.; Li, Q.; Wang, F.; Cheng, Y. Sediment Instability Caused by Gas Production from Hydrate-Bearing Sediment in Northern South China Sea by Horizontal Wellbore: Sensitivity Analysis. *Nat. Resour. Res.* **2025**, *34*, 1667–1699. [\[CrossRef\]](#)
64. Hu, H.; Wang, Z.; Wang, M.; Zeng, M.; Liu, C.; Chen, H. Effects of different water-based fracturing fluids on mechanical properties and energy evolution of deep coal under true triaxial loading. *Phys. Fluids* **2025**, *37*, 016620. [\[CrossRef\]](#)
65. Papavasileiou, K.D.; Michalis, V.K.; Peristeras, L.D.; Vasileiadis, M.; Striolo, A.; Economou, I.G. Molecular dynamics simulation of water-based fracturing fluids in kaolinite slit pores. *J. Phys. Chem. C* **2018**, *122*, 17170–17183. [\[CrossRef\]](#)
66. Soomro, N.A.; Ansari, U.; Shams, B.; Memon, M.K.; Bhutto, D.K.; Rui, Z.; Pan, Y. Experimental assessment of the stability and impact of water-based fracturing fluid with and without Triethanolamine (TEA). *Fuel Commun.* **2025**, *23*, 100137. [\[CrossRef\]](#)
67. Huang, Q.; Liu, S.; Cheng, W.; Wang, G. Fracture permeability damage and recovery behaviors with fracturing fluid treatment of coal: An experimental study. *Fuel* **2020**, *282*, 118809. [\[CrossRef\]](#)
68. Fan, M.; Lai, X.; Tang, M.; Li, J.; Wang, L.; Gao, J. Preparation and properties of a clean, low--damage waterproof locking damage multifunctional integrated water--based fracturing fluid. *J. Appl. Polym. Sci.* **2022**, *139*, e53207. [\[CrossRef\]](#)
69. Wang, L.; Yao, B.; Cha, M.; Alqahtani, N.B.; Patterson, T.W.; Kneafsey, T.J.; Miskimins, J.L.; Yin, X.; Wu, Y.S. Waterless fracturing technologies for unconventional reservoirs-opportunities for liquid nitrogen. *J. Nat. Gas Sci. Eng.* **2016**, *35*, 160–174. [\[CrossRef\]](#)
70. Li, S.; Zhang, S.; Ma, X.; Zou, Y.; Li, N.; Chen, M.; Cao, T.; Bo, Z. Hydraulic fractures induced by water-/carbon dioxide-based fluids in tight sandstones. *Rock Mech. Rock Eng.* **2019**, *52*, 3323–3340. [\[CrossRef\]](#)
71. Hassen, B.; Zotskine, Y.; Gulewicz, D. Hydraulic fracture containment in the Bakken with a synthetic polymer water based fracture fluid. In Proceedings of the SPE Canada Unconventional Resources Conference, Alberta, Canada, 30 October–1 November 2012; p. SPE-162670. [\[CrossRef\]](#)
72. Mahajan, M.; Rauf, N.; Gilmore, T.; Maylana, A. Water Control and Fracturing: A Reality. In Proceedings of the SPE Asia Pacific Oil and Gas Conference and Exhibition, Adelaide, Australia, 11–13 September 2006; p. SPE-101019. [\[CrossRef\]](#)
73. Wei, Z.; Yang, W.; Zhai, C.; Zhang, Z.; Xu, J.; Pan, R. Fracture characteristics and energy dissipation law of shale under water-based impact loads. *Eng. Fract. Mech.* **2024**, *306*, 110240. [\[CrossRef\]](#)
74. Wu, G.; Pan, J.; Anwaier, M.; Wu, J.; Xiao, P.; Zheng, L.; Wang, W.; Meng, X.; Wang, P.; Liu, J.; et al. Effect of nano-SiO₂ on the flowback-flooding integrated performance of water-based fracturing fluids. *J. Mol. Liq.* **2023**, *379*, 121686. [\[CrossRef\]](#)
75. Li, Q.; Han, Y.; Liu, X.; Ansari, U.; Cheng, Y.; Yan, C. Hydrate as a by-product in CO₂ leakage during the long-term sub-seabed sequestration and its role in preventing further leakage. *Environ. Sci. Pollut. Res.* **2022**, *29*, 77737–77754. [\[CrossRef\]](#)
76. Wanniarachchi, W.A.M.; Ranjith, P.G.; Perera, M.S.A. Shale gas fracturing using foam-based fracturing fluid: A review. *Environ. Earth Sci.* **2017**, *76*, 91. [\[CrossRef\]](#)
77. Wilkins, R.; Menefee, A.H.; Clarens, A.F. Environmental life cycle analysis of water and CO₂-based fracturing fluids used in unconventional gas production. *Environ. Sci. Technol.* **2016**, *50*, 13134–13141. [\[CrossRef\]](#) [\[PubMed\]](#)
78. Li, Q.; Zhang, C.; Yang, Y.; Ansari, U.; Han, Y.; Li, X.; Cheng, Y. Preliminary experimental investigation on long-term fracture conductivity for evaluating the feasibility and efficiency of fracturing operation in offshore hydrate-bearing sediments. *Ocean Eng.* **2023**, *281*, 114949. [\[CrossRef\]](#)
79. Jiang, G.; Sun, J.; He, Y.; Cui, K.; Dong, T.; Yang, L.; Yang, X.; Wang, X. Novel water-based drilling and completion fluid technology to improve wellbore quality during drilling and protect unconventional reservoirs. *Engineering* **2022**, *18*, 129–142. [\[CrossRef\]](#)
80. Ghanbari, E.; Dehghanpour, H. The fate of fracturing water: A field and simulation study. *Fuel* **2016**, *163*, 282–294. [\[CrossRef\]](#)
81. Zhang, C.P.; Cheng, P.; Ma, Z.Y.; Ranjith, P.G.; Zhou, J.P. Comparison of fracturing unconventional gas reservoirs using CO₂ and water: An experimental study. *J. Pet. Sci. Eng.* **2021**, *203*, 108598. [\[CrossRef\]](#)
82. Abdelaal, A.; Aljawad, M.S.; Alyousef, Z.; Almajid, M.M. A review of foam-based fracturing fluids applications: From lab studies to field implementations. *J. Nat. Gas Sci. Eng.* **2021**, *95*, 104236. [\[CrossRef\]](#)
83. Qiang, L.i.; Li, Q.; Han, Y. A numerical investigation on kick control with the displacement kill method during a well test in a deep-water gas reservoir: A case study. *Processes* **2024**, *12*, 2090. [\[CrossRef\]](#)

84. Wang, Y.; Li, Q.; Dong, W.; Li, Q.; Wang, F.; Bai, H.; Zhang, R.; Owusu, A.B. Effect of different factors on the yield of epoxy-terminated polydimethylsiloxane and evaluation of CO₂ thickening. *RSC Adv.* **2018**, *8*, 39787–39796. [\[CrossRef\]](#)
85. Zhang, Z.; Mao, J.; Yang, X.; Zhao, J.; Smith, G.S. Advances in waterless fracturing technologies for unconventional reservoirs. *Energy Sources Part A Recovery Util. Environ. Eff.* **2019**, *41*, 237–251. [\[CrossRef\]](#)
86. Li, Q.; Cheng, Y.; Li, Q.; Ansari, U.; Liu, Y.; Yan, C.; Lei, C. Development and verification of the comprehensive model for physical properties of hydrate sediment. *Arab. J. Geosci.* **2018**, *11*, 325. [\[CrossRef\]](#)
87. Guo, Y.; Huang, L.; Li, X. Influence of 3D forced water-based working fluid imbibition on dynamic responses of deep anisotropic shale reservoir. *Int. J. Rock Mech. Min. Sci.* **2025**, *194*, 106195. [\[CrossRef\]](#)
88. Barati, R.; Liang, J.T. A review of fracturing fluid systems used for hydraulic fracturing of oil and gas wells. *J. Appl. Polym. Sci.* **2014**, *131*, 40735. [\[CrossRef\]](#)
89. Zhong, C.; Zolfaghari, A.; Hou, D.; Goss, G.G.; Lanoil, B.D.; Gehman, J.; Tsang, D.C.; He, Y.; Alessi, D.S. Comparison of the hydraulic fracturing water cycle in China and North America: A critical review. *Environ. Sci. Technol.* **2021**, *55*, 7167–7185. [\[CrossRef\]](#)
90. Zhu, D.; Gu, Z.; Guo, F. Evolution of the breakdown pressure and fracture induced by water-/liquid CO₂-based indirect fracturing. *Eng. Fract. Mech.* **2025**, *322*, 111190. [\[CrossRef\]](#)
91. Li, Q.; Cheng, Y.; Ansari, U.; Han, Y.; Liu, X.; Yan, C. Experimental investigation on hydrate dissociation in near-wellbore region caused by invasion of drilling fluid: Ultrasonic measurement and analysis. *Environ. Sci. Pollut. Res.* **2022**, *29*, 36920–36937. [\[CrossRef\]](#)
92. Liu, Y.; Wu, Z.; Weng, L.; Wu, L.; Xu, X.; Liu, Q. Experimental study on the grouting diffusion process in fractured sandstone with flowing water based on the low-field nuclear magnetic resonance technique. *Rock Mech. Rock Eng.* **2023**, *56*, 7509–7533. [\[CrossRef\]](#)
93. Shariatpanahi, S.F.; Strand, S.; Austad, T. Evaluation of water-based enhanced oil recovery (EOR) by wettability alteration in a low-permeable fractured limestone oil reservoir. *Energy Fuels* **2010**, *24*, 5997–6008. [\[CrossRef\]](#)
94. Kondash, A.; Vengosh, A. Water footprint of hydraulic fracturing. *Environ. Sci. Technol. Lett.* **2015**, *2*, 276–280. [\[CrossRef\]](#)
95. Zhao, Y.; Wang, Y.; Tang, L. The compressive-shear fracture strength of rock containing water based on Druker-Prager failure criterion. *Arab. J. Geosci.* **2019**, *12*, 452. [\[CrossRef\]](#)
96. Wanniarachchi, W.A.M.; Ranjith, P.G.; Perera, M.S.A.; Rathnaweera, T.D.; Zhang, D.C.; Zhang, C. Investigation of effects of fracturing fluid on hydraulic fracturing and fracture permeability of reservoir rocks: An experimental study using water and foam fracturing. *Eng. Fract. Mech.* **2018**, *194*, 117–135. [\[CrossRef\]](#)
97. Li, Q.; Li, Y.; Cheng, Y.; Li, Q.; Wang, F.; Wei, J.; Liu, Y.; Zhang, C.; Song, B.; Yan, C.; et al. Numerical simulation of fracture reorientation during hydraulic fracturing in perforated horizontal well in shale reservoirs. *Energy Sources Part A Recovery Util. Environ. Eff.* **2018**, *40*, 1807–1813. [\[CrossRef\]](#)
98. Zhang, R.; Zheng, X.; Li, S.; Jin, K.; Zheng, H.; Wang, L. Environmentally friendly hydraulic fracturing and water-free fracturing technologies. *Int. J. Oil Gas Coal Technol.* **2018**, *17*, 375–390. [\[CrossRef\]](#)
99. Lai, F.; Li, Z.; Wang, Y. Impact of water blocking in fractures on the performance of hydraulically fractured horizontal wells in tight gas reservoir. *J. Pet. Sci. Eng.* **2017**, *156*, 134–141. [\[CrossRef\]](#)
100. Wang, X.; Ge, J.; Ren, Q.; Huang, K.; Ge, H. The failure mode and fracture morphology of shale under dry and water fracturing situation. *Phys. Fluids* **2025**, *37*, 026633. [\[CrossRef\]](#)
101. Tokunaga, T.K.; Omosebi, O.A.; Wan, J. Surfactants are ineffective for reducing imbibition of water-based fracturing fluids in deep gas reservoirs. *Energy Fuels* **2021**, *35*, 11239–11245. [\[CrossRef\]](#)
102. Lv, L.; Lin, J.; Feng, Y.; Wang, W.; Li, S. Coated recombinant Escherichia coli for delayed release of β -mannanase in the water-based fracturing fluid. *Process Biochem.* **2021**, *107*, 121–128. [\[CrossRef\]](#)
103. Gao, J.; Zou, C.; Zhang, X.; Guo, W.; Yu, R.; Ni, Y.; Liu, D.; Kang, L.; Liu, Y.; Kondash, A.; et al. The water footprint of hydraulic fracturing for shale gas extraction in China. *Sci. Total Environ.* **2024**, *907*, 168135. [\[CrossRef\]](#)
104. Du, X.; Carlson, K.H.; Tong, T. The water footprint of hydraulic fracturing under different hydroclimate conditions in the Central and Western United States. *Sci. Total Environ.* **2022**, *840*, 156651. [\[CrossRef\]](#) [\[PubMed\]](#)
105. Wisen, J.; Chesnaux, R.; Wendling, G.; Werring, J. Water footprint of hydraulic fracturing in Northeastern British Columbia, Canada. *Environ. Earth Sci.* **2019**, *78*, 689. [\[CrossRef\]](#)
106. Liu, D.; Li, J.; Zou, C.; Cui, H.; Ni, Y.; Liu, J.; Wu, W.; Zhang, L.; Coyte, R.; Kondash, A.; et al. Recycling flowback water for hydraulic fracturing in Sichuan Basin, China: Implications for gas production, water footprint, and water quality of regenerated flowback water. *Fuel* **2020**, *272*, 117621. [\[CrossRef\]](#)
107. Raimi, D. Comment on “The intensification of the water footprint of hydraulic fracturing”. *Sci. Adv.* **2020**, *6*, eaav2110. [\[CrossRef\]](#) [\[PubMed\]](#)
108. Wu, X.; Xia, J.; Guan, B.; Liu, P.; Ning, L.; Yi, X.; Yang, L.; Hu, S. Water scarcity assessment based on estimated ultimate energy recovery and water footprint framework during shale gas production in the Changning play. *J. Clean. Prod.* **2019**, *241*, 118312. [\[CrossRef\]](#)
109. Ikonnikova, S.A.; Male, F.; Scanlon, B.R.; Reedy, R.C.; McDaid, G. Projecting the water footprint associated with shale resource production: Eagle Ford shale case study. *Environ. Sci. Technol.* **2017**, *51*, 14453–14461. [\[CrossRef\]](#)

110. Li, Q.; Wang, Y.; Wang, F.; Li, Q.; Kobina, F.; Bai, H.; Yuan, L. Effect of a modified silicone as a thickener on rheology of liquid CO₂ and its fracturing capacity. *Polymers* **2019**, *11*, 540. [\[CrossRef\]](#)
111. Nicot, J.P.; Scanlon, B.R.; Reedy, R.C.; Costley, R.A. Source and fate of hydraulic fracturing water in the Barnett Shale: A historical perspective. *Environ. Sci. Technol.* **2014**, *48*, 2464–2471. [\[CrossRef\]](#)
112. Rosa, L.; Rulli, M.C.; Davis, K.F.; D’Odorico, P. The water—Energy nexus of hydraulic fracturing: A global hydrologic analysis for shale oil and gas extraction. *Earth’s Future* **2018**, *6*, 745–756. [\[CrossRef\]](#)
113. Zhang, D.; Tingyun, Y.A.N.G. Environmental impacts of hydraulic fracturing in shale gas development in the United States. *Pet. Explor. Dev.* **2015**, *42*, 876–883. [\[CrossRef\]](#)
114. Gilmore, K.R.; Hupp, R.L.; Glathar, J. Transport of hydraulic fracturing water and wastes in the Susquehanna river basin, Pennsylvania. *J. Environ. Eng.* **2014**, *140*, B4013002. [\[CrossRef\]](#)
115. Alessi, D.S.; Zolfaghari, A.; Kletke, S.; Gehman, J.; Allen, D.M.; Goss, G.G. Comparative analysis of hydraulic fracturing wastewater practices in unconventional shale development: Water sourcing, treatment and disposal practices. *Can. Water Resour. J./Rev. Can. Ressour. Hydr.* **2017**, *42*, 105–121. [\[CrossRef\]](#)
116. Zemlick, K.; Kalhor, E.; Thomson, B.M.; Chermak, J.M.; Graham, E.J.S.; Tidwell, V.C. Mapping the energy footprint of produced water management in New Mexico. *Environ. Res. Lett.* **2018**, *13*, 024008. [\[CrossRef\]](#)
117. Li, Q.; Cheng, Y.; Li, Q.; Zhang, C.; Ansari, U.; Song, B. Establishment and evaluation of strength criterion for clayey silt hydrate-bearing sediments. *Energy Sources Part A Recovery Util. Environ. Eff.* **2018**, *40*, 742–750. [\[CrossRef\]](#)
118. Fu, C.; Liu, N. Waterless fluids in hydraulic fracturing—A review. *J. Nat. Gas Sci. Eng.* **2019**, *67*, 214–224. [\[CrossRef\]](#)
119. Du, J.; Whittle, A.J.; Hu, L.; Divoux, T.; Meegoda, J.N. Mechanical degradation of Longmaxi shale exposed to water-based fluids and supercritical carbon dioxide. *J. Rock Mech. Geotech. Eng.* **2025**, *17*, 3378–3394. [\[CrossRef\]](#)
120. Yang, B.; Wang, H.; Wang, B.; Shen, Z.; Zheng, Y.; Jia, Z.; Yan, W. Digital quantification of fracture in full-scale rock using micro-CT images: A fracturing experiment with N₂ and CO₂. *J. Pet. Sci. Eng.* **2021**, *196*, 107682. [\[CrossRef\]](#)

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