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Perspective

Experimental and numerical simulation technique for hydraulic fracturing of shale formations

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Abstract:
Hydraulic fracturing is crucial for extracting shale oil and gas. This technique involves creating fractures in rock formations to enhance reservoir development efficiently. Due to the complexity of shale rock, it is important to conduct multiscale investigations into the fracturing process. Despite extensive research, the technology for deep-underground shale hydraulic fracturing continues to advance as it moves deeper underground. This paper explores the existing technical challenges of shale fracturing, review the current status of physical experiments and numerical simulations, and highlight the importance of multiscale numerical simulation methods. Meanwhile, an integrated approach to optimizing fracturing designs for field cases is introduced. Finally, this paper summarizes the challenges and opportunities in shale hydraulic fracturing, aiming to provide fresh insights into the advancements of hydraulic fracturing technology.

1. Introduction

As an essential supplement to conventional energy, the large-scale development of shale gas has significantly influenced the adjustment and transformation of China's energy structure. Geological exploration data reveal that shale reservoirs are characterized by deep burial, low porosity, low permeability, and strong non-homogeneity, among other significant features (Tan et al., 2023). These reservoirs are inherently poor at transporting oil and gas on their own. Therefore, they require the creation of an artificial fracture network through hydraulic fracturing and other reservoir modification technologies. This is essential to enhance the production and transportation of oil and gas, facilitating the commercial development of shale gas.

Over the past decade, the development of horizontal drilling and multi-stage hydraulic fracturing technologies has significantly boosted shale gas production in the United States, leading to shifts in the international natural gas market and the global energy landscape. In response, major resource-rich countries, including China, have intensified their efforts in exploring and developing shale gas. However, research indicates that large-scale exploitation of shale oil and gas in China continues to encounter significant technical challenges. A key issue that remains to be addressed is the effective use of hydraulic fracturing technology to create a functional fracture system.

This work explores the technical challenges of hydraulic fracturing in non-homogeneous shale reservoirs, providing a brief overview of the current status and achievements in this area. The key factors that affect the effectiveness of hydraulic fracturing are summarized, and the mechanism of hydraulic fracture initiation and expansion in shale are elucidated (Fig.

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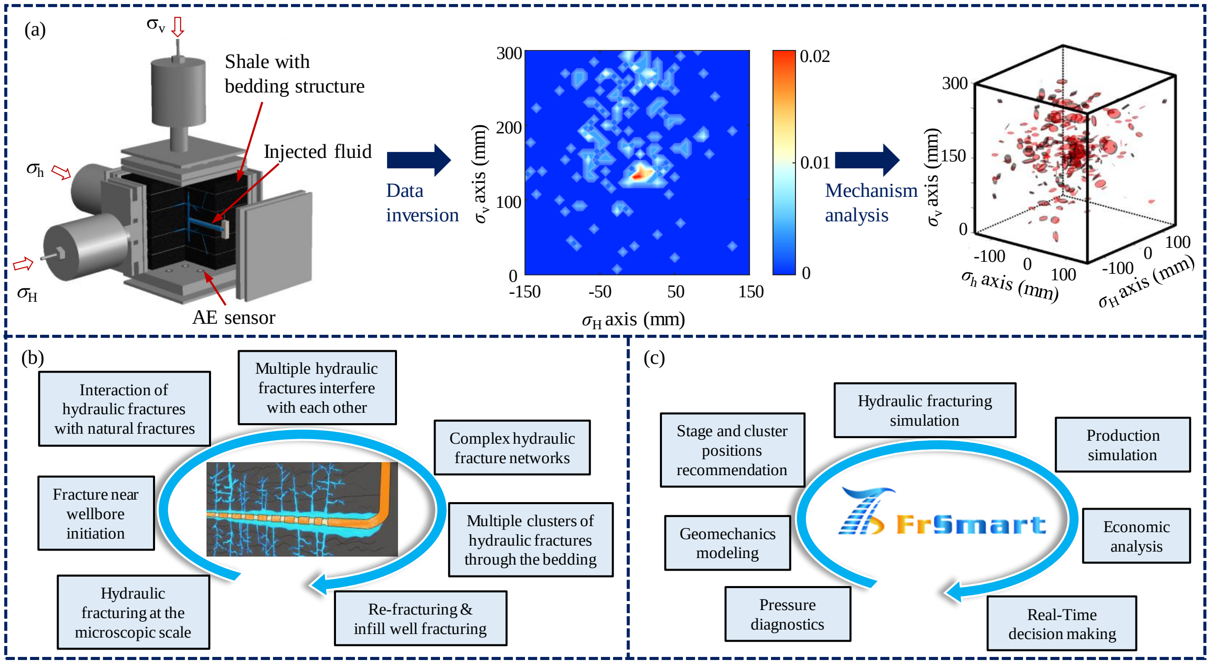

Fig. 1. Hydraulic fracturing in shale: experiments, numerical simulation, and integrated fracture optimization design method. (a) Experimental device for hydraulic fracturing in shale, (b) numerical model of multi-scale hydraulic fracturing and (c) hydraulic fracturing design optimization based on the integrated geology-engineering workflow in FrSmart.

1). Additionally, this paper introduces an integrated fracture optimization design method, offering new perspectives for designing modifications to shale reservoir fracturing and promoting the efficient development of shale oil and gas.

2. Major engineering problems in shale

Forming a complex artificial fracture network through volumetric fracturing is a critical technical aspect for efficient shale gas development. A significant method for establishing such a network involves utilizing high net pressures to fully exploit naturally weak surfaces like bedding plane and natural fracture. However, the Sichuan shale gas reservoir in China, compared to North America's deep Haynesville shale (Chen and Zeng, 2016), presents additional complexities due to its tectonic setting, high temperature and pressure, extensive natural fractures, and high differential stress, making fracturing more challenging (refer to Table 1). The specific difficulties encountered during the fracking process include: (1) High critical net pressure needed to open fractures due to significant differences in horizontal principal stresses and stronger shale, resulting in low fracture complexity that requires enhancement; (2) Natural fractures causing multi-cluster hydraulic fractures to expand unevenly, with cluster efficiency below 70% (Zang et al., 2022), and low inter-cluster mobilization; (3) Under strike-slip stress conditions, hydraulic fractures tend to steer along bedding joints, limiting the longitudinal expansion through the bedding and thus reducing the effective longitudinal mobilization of resources.

3. Experiments and acoustic emission monitoring in hydraulic fracturing

Hydraulic fracturing experiments are essential for understanding the mechanisms of rock fracturing under controlled conditions. These experiments play a crucial role in exploring the underlying mechanics, optimizing fracturing processes, and evaluating the performance of fracturing fluids and proppants. Devices developed for these experiments, ranging from pseudo-triaxial to true triaxial systems, allow researchers to replicate complex underground stress conditions and observe fracture initiation and propagation in various rock types (Tan et al., 2017, 2019). These devices have led to the research of simulating a wide range of geological conditions. These include true triaxial cells for applying independent stresses along three axes, scaled models to study the impact of fracturing fluid viscosity, proppant types, and injection rates on fracture propagation (Li et al., 2020).

Observation techniques for hydraulic fracture growth offer diverse insights into the fracturing process. Analyzing injection pressure variations can highlight fracture initiation and growth phases, with certain fluctuations indicating specific events. Fracture tracers in the fracturing fluid reveal the extent of fracture networks and how fluids distribute within the rock matrix. CT scanning, providing high-resolution, three-dimensional (3D) images, captures the internal structure of rocks before and after fracturing. It offers unique insights into the fracture network and rock interactions (Zhai et al., 2020). Ultrasonic imaging and acoustic emission monitoring are key for real-time monitoring, which can detect energy releases from crack formations (Wang et al., 2016). Moreover, recent

Table 1. Comparison table of shale geo-engineering parameters in different regions at home and abroad.

Region	Changning	Weiyuan	Luzhou	Western Chongqing	Haynesville
Depth (m)	2,500-3,000	2,000-3,500	3,200-4,500	3,500-4,500	3,800-4,200
Structural complexity	More complicated	Simple	Complex	Complex	Simple
Fracture development	More developed	More developed	Development	More developed	Underdevelopment
Continuous thickness (m)	6-12	4-10	7-18	Zhu203: 5-8.8 Huang202: 7-16 Da an: 7-13	/
Formation temperature (°C)	87-110	128	135-155	87-95	119-137
Horizontal stress difference (MPa)	12-15	8-18	14-21	19-22	3-6
Young's modulus (GPa)	18-56	30-56	20-60	19-61	6.9-24

hydraulic fracturing experiment studies have improved our understanding of fracture tip progression using distributed acoustic sensing data.

Among various experimental methods, true triaxial hydraulic fracturing experiments combined with acoustic emission monitoring are key laboratory methods for investigating hydraulic fracture spread in shale reservoirs. These experiments often use cubic samples (300 mm in size or larger) and apply true triaxial stresses to mimic natural formation stress states (Tan et al., 2020). The system injects fluid at a constant rate, measuring wellhead fluid pressure close to the bottom hole pressure. Challenges in acoustic emission include high-frequency system design, effective signal identification, and error reduction in anisotropic rock localization (Wu et al., 2022). Typically, acoustic emission monitoring systems use multiple probes on the rock sample.

Acoustic emission source mechanism analysis, borrowing concepts from earthquake mechanics, uses the moment tensor method to study rock fracturing mechanics. This analysis categorizes fractures into tensile, shear, or mixed types. In hydraulic fracturing, understanding the tensile-shear nature of fractures is crucial. Interactions between hydraulic and natural fractures in rock are revealed through acoustic emission moment tensor components (Ohtsu, 2016). These interactions include penetration, capture, deflection, and acoustic emission localization results, suggesting varying fracture types in different rock formations. Experimental results show that near the wellhead, tensile fracturing dominates, but further away, shear fracturing becomes more prevalent due to interaction with natural fractures (Wu et al., 2019). This shift influences the fracture network's complexity and its propagation pattern.

Acoustic emission monitoring and true triaxial hydraulic fracturing experiments are crucial for comprehending fracture mechanics in shale reservoirs. Although this method has been widely applied, there is a lack of standardized calibration processes for acoustic emission sensors. Additionally, there is insufficient validation of localization results and source mechanism inversion outcomes. The absence of error analysis for these results is also a gap that needs to be addressed in future research.

4. Numerical modeling of hydraulic fracturing

Hydraulic fracture propagation presents multi-scale characteristics, and the complexity of this phenomenon prompts us to think deeply about the fracture propagation mechanism from multiple perspectives (Huang et al., 2022). However, due to the limitations of physical experimental equipment, it is difficult to capture the dynamic expansion paths of fractures accurately, and the data do not provide a good reduction of the hydraulic fracture situation in the field. Recently, the rapid development of numerical simulation technology has provided an effective and accurate means to study the dynamic expansion of hydraulic fractures. Relying on various types of numerical simulation methods, the mechanism of fracture expansion at multiple scales has been gradually clarified (Huang et al., 2023a).

The study on the microscopic level is of great significance to reveal the interaction between hydraulic fractures and mineral particles and to explain the principle of fracture propagation. The random distribution of mineral composition and particle shape in the rock further aggravates the heterogeneity of the reservoir, which makes the expansion of hydraulic fractures show strong asymmetry (Dou and Wang, 2022). Various interaction modes between hydraulic fractures and mineral particles further enhance the tortuous degree of fracture morphology (Huang et al., 2023a). In general, high-displacement, high-viscosity hydraulic fractures are more likely to directly penetrate mineral particles, but they also trigger higher fracture pressures (Dong et al., 2023). In addition, high mineral interface stiffness will hinder the expansion path of hydraulic fractures, resulting in limited hydraulic fracture propagation height (Aimene et al., 2019).

As one of the important sources of non-planar extension and branching extension of hydraulic fractures, natural fractures may be reactivated during their interaction with hydraulic fractures, which leads to changes in the direction of hydraulic fracture propagation and generates complex fracture patterns such as bifurcation and bending (Zhang et al., 2022). There are many interaction modes between hydraulic fractures and natural fractures, including capture, deflection through, and straight through (Weng, 2015). Under high displacement, high viscosity, and high-stress differential conditions, hydraulic fractures are more likely to directly cross natural fractures (Kamali et al., 2023). The effect of natural fracture networks on hydraulic fracture propagation is more meaningful in engineering practice than that of a single natural fracture. The existence of natural fracture network greatly increases the curvature of the fracture propagation path and intensifies the complexity of fracture morphology (Cao et al., 2022). Accurately grasping the interaction mechanism between hydraulic fractures and natural fractures, and efficiently utilizing the original natural fractures system in the reservoir are still the key technical challenges to improve the effectiveness of hydraulic fracturing reservoir modification.

The discontinuities in the geology, rock mechanical properties, and stresses vary spatially, leading to a much higher complexity of fracture propagation during hydraulic fracturing, and fracture expansion can proceed in any direction in three dimensions (Zhang et al., 2021). It has been shown that the near-wellbore stress field and reservoir rock toughness mainly control fracture initiation (Huang et al., 2020). However, wellbore excavation and perforation injection in fracturing often lead to stress concentration phenomenon, which results in complex stress differences in the near-wellbore area and makes the fracture initiation effect difficult to predict (Michael and Gupta, 2021). Compared with the multiple planar fractures produced by directional perforation, spiral perforation is prone to produce complex fracture morphology with the interweaving of planar and spiral fractures, and the direction of fracture propagation is mainly controlled by the direction of the minimum principal stress (Huang et al., 2023b).

Fracture propagation height is one of the critical factors in judging the effectiveness of fracture modification, while the commonly developed bedding plane in reservoirs often restricts the vertical extension of hydraulic fractures, making reservoir modification inefficient (Zeng et al., 2023). When hydraulic fractures intersect with bedding planes, they will be captured at the bedding planes and form T-shaped fractures, or they will deflect after extending along the bedding planes for a certain distance, or they will directly cross the bedding planes. The interaction is influenced by many factors, including in-situ stress, rock properties, bedding characteristics, and field pumping parameters. However, there are differences in fracture propagation guidelines under different propagation regimes. How to effectively evaluate the fracture penetration criterion under different combinations of fracturing parameters remains an urgent challenge.

Although numerical simulation of hydraulic fracturing has achieved many successes, there are still many shortcomings, such as the mechanism of the interaction between hydraulic fractures and natural structural surfaces has not been fundamentally solved. In addition, the mitigation of the negative effects associated with the stress-shadow effect remains an essential issue in the context of multi-stage hydraulic fracturing technology employed for horizontal wells. Meanwhile, the behavior of multiple non-planar hydraulic fractures expanding simultaneously considering the fracturing fluid flow process is also a difficult problem to solve in theoretical analysis and numerical simulation.

5. Geology-engineering integration modeling

As mentioned in previous sections, physical simulation experiments help to reveal the mechanisms of hydraulic fracturing, and numerical simulation helps to elucidate the influence of various parameters on hydraulic fracturing. They together form the solid theoretical foundation for designing field hydraulic fracturing operations. The output of a hydraulic fracturing operation is affected by both geomechanics and engineering parameters. The geomechanics parameters, such as elastic mechanical parameters and in-situ stresses, are much more heterogeneous in unconventional reservoirs than those in conventional reservoirs, therefore it is crucial to construct accurate geomechanics models before conducting hydraulic fracturing simulations. It has become a consensus to utilize geology-engineering integration workflow which tightly connect geomechanics modeling and hydraulic fracturing simulation in the hydraulic fracturing design optimization of unconventional reservoirs.

The constructing geomechanics models can provide geological and mechanical backgrounds for hydraulic fracture simulation. Depending on the number of dimensions of input and output data, the methods of constructing geomechanics models can be divided into two categories. The first category is single-well geomechanics modeling, where log curves, experiment data, and field test data from a single well are used to determine the elastic mechanical parameters and in-situ stresses along the well trajectory. Since rocks can generally be considered elastic when wave propagates in them, the method to compute elastic mechanical parameters is a universal one derived from the elastic wave equation (Fjar et al., 2008). When it comes to in-situ stresses, it is a common practice to compute the vertical stress by integrating the density log. However, the methods to determine horizontal principal stresses are rather empirical. The second category of geomechanics modeling method is 3D modeling based on structural models, well log curves from multiple wells, and sometimes seismic data. On this basis, the 3D distribution of elastic mechanical parameters can be obtained by interpolation of log data from multiple wells or by seismic inversion. Combined with the above data, given stress or displacement boundary conditions, the 3D spatial distribution of in-situ stresses can be simulated to get the geomechanics models (Singha and Chatterjee, 2015).

Hydraulic fracturing simulation is performed after geological modeling. Compared with that for conventional reservoirs, the hydraulic fracturing simulation for unconventional reservoirs is much more complex in the aspects of both geology and engineering. In the aspect of geology, unconventional reservoirs, particularly shale oil and gas reservoirs, are often characterized by high vertical heterogeneity and densely distributed natural fractures. To consider the influence of vertical heterogeneity, it is preferable to use 3D fracture propagation models instead of two-dimensional plane strain models or pseudo-three-dimensional models. The statistical methods can be used to construct a discrete natural fracture model to consider the influence of natural fractures (Lang and Guo, 2013). Based on this model, the influence of natural fractures on the propagation of hydraulic fractures can be described by various criteria.

Based on the geology-engineering integration workflow, the hydraulic fracturing design software FrSmart has been released by China National Petroleum Corporation (CNPC) in 2023. The current version of the software incorporates both single-well and 3D geomechanics modeling methods in its geomechanics module, and has, in its hydraulic simulation module, a 3D fracture simulator which can model planar and non-planar 3D hydraulic fracture propagation and a complex fracture simulator which can model hydraulic fracture propagation under the influence of multiple natural fractures. FrSmart is China's first geology-engineering integrated hydraulic fracturing design software, which has been applied to the hydraulic fracturing design of over 300 wells. In the future, the software will keep evolving in the directions such as accelerating large-scale, high-resolution fracturing simulations and offering artificial intelligence solutions.

6. Challenges and perspectives

The rapidly evolving numerical modeling technology for hydraulic fracturing has marked significant strides in both academic research and practical field applications. Despite these advances, the increasing global energy demand continues to present formidable challenges in this area. Key developmental focuses for numerical simulation of hydraulic fracturing include:

1) Interaction mechanism clarification: The interaction between hydraulic fractures and natural structural surfaces, influenced by 3D rock anisotropy and strength transformations, remains inadequately understood. There is a clear need for more effective numerical models that can accurately represent rock anisotropy.
2) Stress shadowing effects: The stress shadowing phenomenon in perforation fracturing is still poorly comprehended, and accurately modeling the behavior of multiple nonplanar hydraulic fractures is challenging. Developing strategies to counteract the adverse effects of stress shadowing is crucial.
3) Simulation accuracy: A significant discrepancy exists between the outcomes of numerical simulations and empirical observations of fractures in real-world settings. Current simulations often rely on oversimplified models that fail to capture the complexity of fracture dynamics, resulting in substantial inaccuracies.
4) High-pressure and high-temperature conditions: As the depth of reservoir development increases, so do the challenges associated with higher temperatures, greater insitu stresses, and increased pore pressures. The injection of cold fluids during fracturing creates a thermal shock effect, further complicating the accurate simulation of hydraulic fracture propagation paths under these extreme conditions. Advancements in thermal-fluid-solid numerical simulation technologies are necessary to enhance our understanding of fracture propagation mechanisms in these complex environments.
5) Computational efficiency improvement: The complexity of models used in hydraulic fracturing simulations is continually increasing, amplifying the need for faster computation times. Field engineers, often required to produce multiple designs daily, would greatly benefit from enhanced algorithms and the integration of cloud computing technologies to speed up simulation processes.

7. Conclusions

This paper review and conclude that acoustic emission monitoring and true triaxial hydraulic fracturing experiments are indispensable for understanding fracture mechanics in shale reservoirs. While these methods have seen widespread application, they suffer from a lack of standardized calibration processes for acoustic emission sensors. There is also a notable deficiency in the validation of localization results and source mechanism inversion outcomes, compounded by an absence of error analysis for these results, identifying a significant research gap that requires attention.

Furthermore, this paper reviews the current status of hydraulic fracturing numerical simulation research. The effect of rock inhomogeneity on hydraulic fracture extension is discussed further, and the interaction mechanism between hydraulic fracture and natural fracture is clarified, as well as the mechanism of near-well fracture initiation in the process of shot hole fracturing.

Additionally, this paper addresses the significant challenges encountered by hydraulic fracturing design software when applied to unconventional reservoirs characterized by substantial heterogeneity and dense natural fracture networks. To effectively address these challenges, an integrated geology-engineering hydraulic fracturing design workflow is recommended. This review assesses the methodologies used in this integrated approach, aiming to offer comprehensive solutions for the complexities of hydraulic fracturing in unconventional reservoirs.

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Conflict of interest

The authors declare no competing interest.

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