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Perspective

Advances, challenges, and opportunities for hydraulic fracturing of deep shale gas reservoirs

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Abstract:
Although significant progress has been made in the development of shallow natural gas, the exploitation of deep shale gas continues to face numerous challenges. Therefore, conducting research on deep shale gas extraction is crucial. The efficient exploitation is contingent upon a comprehensive understanding of the mechanical properties, fracturing behaviors, and transformation processes of deep reservoir formations. This paper initially delineates the geo-mechanical characteristics and key development challenges associated with deep shale gas reservoirs. It subsequently reviews recent advancements in laboratory experiments, numerical simulations, and field technologies. Finally, suggestions and strategies are proposed to enhance the efficiency of deep shale gas development. The perspectives offered in this paper aim to provide new insights into optimizing exploration and production in deep and complex geological environments.

1. Introduction

With the increase of exploration and development efforts, China's natural gas development is shifting from shallow to deep, from conventional to unconventional, and the newly discovered reserves of deep natural gas resources are further increasing (Zang et al., 2024). Notably, the first section of the Wufeng Formation Longmaxi Formation in the Sichuan Basin is rich in shale gas resources, with a proven geological resource of 21.9×10^{12} m^3. Deep shale gas with a depth of over 3,500 meters accounts for up to 86% and has a resource foundation of producing shale gas of over 300×10^8 m^3 per year. However, the low porosity and permeability of deep shale necessitate the construction of complex artificial fracture networks to achieve efficient extraction and development.

Compared to shallow and medium-depth reservoirs, the development of deep natural gas development presents significant challenges. High temperature (120-150 °C), high stress (80-100 MPa), substantial stress differentials (15-25 MPa), and the presence of complex natural fractures complicate the nonlinear deformation and failure of deep rock more difficult. Hydraulic fracturing in these environments requires high rupture pressures thereby complicating the formation of complex fracture networks. Additionally, deep shale gas wells in the Luzhou block of the Sichuan Basin are susceptible to issues such as casing deformation, pressure breakout, low estimated ultimate recovery, and high drilling and completion costs. These challenges hinder the effective development of deep shale gas. Critical obstacles include the reproducing of in-situ high-temperature and high-stress environment, understanding fracture propagation in complex geological conditions, and advancement of effective methods for fracture construction and safe fracturing control.

This paper takes the development of natural gas such as deep shale gas in southern Sichuan as an example, briefly summarizes the progress and achievements in laboratory phys-

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ical simulation, numerical simulation technologies, and on-site fracturing technology. Then, the limitations and understanding of existing research are discussed, and the development direction of development technology is pointed out. The perspectives offered new insights for the ongoing research and technological development of natural gas extraction in complex geological environments.

2. Laboratory physical simulation

The preparation of specimens with complex structures is prerequisite for laboratory physical simulation. Traditional preparation methods are as follows: 1) Obtaining specimens containing structural planes from the site, which maximally reflects the characteristics of the structural planes on site, but it is difficult to conduct experiments again after the same sample is damaged; 2) Using similar materials to pour model specimens containing specific structural planes can replicate the structural planes, but there is a significant difference from the actual structural planes; 3) The Brazilian splitting method was used to prepare specimens containing fractured structural planes, but the structural planes obtained each time were relatively random and could not be replicated. Given the gradual maturity of three-dimensional (3D) scanning, engraving technology, and other technologies (Ding et al., 2020; Riquelme et al., 2022), the reconstruction method of the original state of rock discontinuity based on a variety of new technologies may ensure the consistency of surface mechanical properties between the original structure and the reconstructed structure.

Advanced laboratory testing systems are essential for investigating the deformation and failure characteristics of rocks in high-temperature and high-pressure environments (Li and Bhushan, 2002). The systems built in recent years include a real-time high-temperature true triaxial testing system, a hydraulic fracturing testing system, and a pseudo triaxial testing system, all designed to replicate the in-situ conditions of deep reservoirs. These systems enable the examination of critical phenomena such as fluid flow and the transition from brittle to ductile failure in rocks under extreme stress and temperature. Furthermore, the deep rock mechanics laboratory has improved the accuracy of rock mechanics parameter measurements, thereby meeting the specific testing requirements of deep energy engineering.

The physical simulation of true triaxial fracturing in a laboratory setting under high-temperature and high-pressure conditions serves as a crucial methodology for investigating the spatial distribution and propagation mechanisms of hydraulic fractures. Current physical modeling techniques facilitate true triaxial stress loading on cubic specimens with a side length of 1,000 mm, in conjunction with external heating up to 600 °C on cubic specimens measuring 300 mm (Yang et al., 2024). These methodologies effectively simulate the high-temperature conditions and 3D unequal stress states found in deep formations. However, a significant limitation arises from the challenge of accurately matching the stress magnitudes applied to the specimens with those experienced in actual deep reservoirs. Consequently, true triaxial fracturing equipment with real-time, high temperature, high pressure, and other functions has become a necessary condition for laboratory fracturing physical simulation of deep shale (Mao et al., 2017). Specifically, this equipment needs to ensure the application of environmental loads such as high temperature (up to 350 °C) and high stress. Furthermore, it also needs to be equipped with acoustic emission sensors, acoustic devices, digital image correlation, and optical fiber monitoring equipment, to measure the key parameters in the process of fracture propagation in real-time.

Monitoring fractures and other phenomena during the experimental process is a critical approach for elucidating experimental patterns. For small-scale samples, CT and other techniques are typically employed to characterize the propagation morphology of fractures following reservoir fracturing (Tan et al., 2024; Zhou et al., 2024). For large-scale samples, it is usually necessary to introduce a color developer into the fracturing fluid and use physical methods to knock open the fractured sample. By observing the distribution of the color developer, the propagation of the fracturing fracture can be characterized (Jiang et al., 2019). Although these two methods can characterize the distribution of fractures after fracturing, they do not provide insights into the propagation process of fractures during the fracturing process. To address this limitation, acoustic emission monitoring technology is utilized to infer the propagation of fractures during the fracturing process. This method enables real-time characterize of fracture distribution, although it is important to note that technical errors may arise during the inversion process. Therefore, a comprehensive approach that integrates multiple monitoring techniques may be necessary to enhance the accuracy and reliability of fracture propagation assessments in laboratory experiments.

3. Numerical simulation technology

The characterization and reconstruction of non-planar fractures are essential for advancing the study of deep shale gas development. These processes are widely applicable to the characterization and reconstruction of interface structures such as natural fractures before fracturing, artificial fractures during fracturing, and the study of reservoir oil well productivity after fracturing transformation (Sherratt et al., 2021; Huang et al., 2024). Generally, it can be achieved through theoretical approaches including empirical judgment, statistical analysis, fractal geometry, and topological geometry. Early parameters and methods are mainly suitable for characterizing single or plane fractures, and there are some stability problems in measurement results (Wu et al., 2024). Therefore, improving the accuracy and stability of the existing measurement technology is the premise to ensure its wide use. In addition, considering that digital image processing techniques have become increasingly prevalent in recent researches (Shi et al., 2024), thus it is necessary to consider the connectivity of fracture structures within voxel space in future investigations.

The mechanical heterogeneity of reservoir rock masses is significantly influenced by the distribution of various minerals, leading to phenomena such as layered mechanical heterogeneity and mechanical heterogeneity affected by multiple mineral components (Zou et al., 2020; Khan et al., 2023). While the modeling of layered reservoirs has achieved considerable maturity, the influence of non-planar features at the interfaces of these reservoirs has received insufficient attention in contemporary research. In addition, modeling the mechanical heterogeneity associated with multiple mineral components presents greater complexity, as the non-uniform distribution of mechanical parameters is often represented through statistical distribution models. However, accurately characterizing the morphology and spatial distribution of distinct minerals are extremely complex and requires further in-depth research.

Upon completing the characterization of complex fracture structures and mechanical heterogeneity, it becomes feasible to construct geometric and attribute models that more accurately reflect the true geological structure and mechanical parameter distribution of the reservoir. Subsequently, conventional fracturing models can be further constructed for numerical simulation research and prediction of fracturing. Unfortunately, with the optimization and improvement of construction technology, fracturing techniques such as multi-cluster, temporary plugging, and dense cutting have been proposed. Although the multi-cluster fracturing simulation has made great progress, there is still great room for improvement in modeling techniques such as more complex dense cutting techniques and temporary blocking simulation methods.

4. Field technology

The evaluation of geological and engineering "sweet spots" is crucial for the effective design of unconventional natural gas reservoir development. Existing brittleness evaluation methods mainly rely on Laboratory experiments and focus on mineral composition and rock mechanics (Wu et al., 2023; Zhao et al., 2024). The mineral composition method allows for quick brittleness index calculations using empirical formulas, but it has limited accuracy due to single influencing factors. Conversely, rock mechanics testing provides high accuracy; however, it is time-consuming, expensive, and restricted to the specific target layer. Recent advancements have incorporated factors such as diagenesis, pore structure, fracture development, and geo-stress into brittleness evaluations. However, rock mechanics-based compressibility methods overlook diagenetic conditions and the correlation between rock strength and strain, reducing accuracy under complex stress. Moreover, comprehensive compressibility evaluation methods are complex and overlook vertical lithology differences in reservoirs. Therefore, it is imperative to consider vertical variations in reservoir characteristics and achieve more accurate compressibility assessments.

In the field of fracturing materials, North America has prioritized cost reduction and the development of specialized function proppants, with a particular focus on finer granular proppants and advanced materials. In China, quartz sand has replaced ceramic proppant in fracturing fluids and a temporary plug system using soluble materials has emerged. However, CO_2 dry fracturing and functional materials for complex conditions remain in experimental stages (Gupta and Verma, 2023). Meanwhile, artificial fracture monitoring, including micro-seismic and fiber-optic methods, is mature in North America, and integrated systems are widely applied. China lags in hardware, data quality, and technology integration, primarily using single monitoring techniques without multi-source evaluation systems.

Regarding fracturing technology, North America has undergone three rounds of iterative upgrades, with major process technologies primarily established and parameter templates primarily finalized (Michael et al., 2020). From the initial introduction of the technology to the localization of the technology in China, the 1.0 version of the volumetric fracturing process technology has been developed. Currently, with the 2.0 version of the volumetric fracturing process technology as the leader, a system of shale gas fracturing technology that matches the geological features of China has been tentatively established. However, the adaptability of process techniques and the ability to prevent and control complex problems in formations with complex geostrategic stresses and developed fractures still need to be further improved.

5. Suggestions and countermeasures

Deep natural gas reservoirs are characterized by well-developed fracture structures, but the rock has high compressive strength and closure stress, large stress differences, and difficulty in forming complex fracture networks through fracturing. Based on the development theory and technology of shallow natural gas reservoirs, there are problems such as weak targeting of process parameters, small transformation volume, and low complexity of fractures, resulting in unsatisfactory fracturing effects. Future efforts should aim at achieving an optimal balance between technology and economy based on the geological and engineering parameters of different blocks and to apply geological and engineering integration methods to obtain the volume fracturing technology of unconventional natural gas reservoirs horizontal wells. Afterwards, some important theoretical techniques and methods should be obtained. For example, Complex fracture network construction theory and optimization design method suitable for deep and ultra-deep natural gas development. Multi cluster fracture balanced propagation technology based on temporary plugging technology for high-stress difference environment. The complexity control technology of enhanced fracture network based on plugging optimization method. Optimization technology for fracturing process in fracture development zones with the aim of reducing the risk of causing damage and pressure breakthrough.

6. Conclusions

Deep shale gas is a crucial strategic replacement resource for China's natural gas storage and production in the future. However, the high temperatures, high pressure, complex geological and tectonic environments associated with deep layer introduces new problems and challenges constantly appear in both the basic theories and technologies of fracturing. In this paper, relevant advances and limitations in laboratory experiments, numerical simulations, and field technologies for deep gas development are reviewed and summarized. Then, technical recommendations and countermeasures for the development of deep and complex geological gas reservoirs are provided. In the future, the basic research should emphasize integrated resource evaluation of deep shale gas, as well as the accurate monitoring and identification technology of multi-scale fracture and natural fracture development zones under tectonic effects. Afterward, supporting fracturing technology suitable for deep shale development can be further developed based on the proven mechanism of hydraulic fracture propagation in a deep complex environment. For example, deep shale gas geological engineering double sweet spot evaluation technology, multi-scale fracture logging-seismic evaluation technology in complex tectonic zones, multi-fracture balanced extension technology, and functional fracturing fluids for temporary blocking fracturing. Finally, these efforts aim to create a three-dimensional transparent model of shale gas reservoirs, facilitating the achievement of exploration and development goals of "accurate visibility, well stimulation, and easy extraction" can be achieved.

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Conflict of interest

The authors declare no competing interest.

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