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Perspective

Reservoir stimulation for unconventional oil and gas resources: Recent advances and future perspectives

Qinzhuo Liao[1], Bin Wang[1]*, Xiang Chen[2,3], Peng Tan[4]

[1]National Key Laboratory of Petroleum Resources and Engineering, China University of Petroleum (Beijing), Beijing 102249, China
[2]National Key Laboratory of Oil and Gas Reservoir Geology and Exploitation, Southwest Petroleum University, Chengdu 610500, China
[3]Petrolum Engineering School, Southwest Petroleum University, Chengdu 610500, China
[4]CNPC Engineering Technology R&D Company Limited, Beijing 102206, China

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Abstract:
The first Geo-Energy Frontier Forum with the theme of “opportunities and challenges for geo-energy exploration and development” was successfully held in Wuhan, recently. The forum included 32 sessions, mainly focused on four directions: geo-energy development and reserve, petroleum geophysical exploration, oil and gas geology, and field development engineering. This paper summarizes the key findings in the 22nd session titled “Reservoir stimulation for unconventional oil and gas resources”. A total of 17 experts and scholars participated in the presentations, covering a wide range of topics in unconventional oil and gas resources development. This research collectively highlighted the significance of reservoir stimulation techniques in unconventional oil and gas resource development, including research progress in fracture network modeling techniques, fluid pressure, rock mechanics, fracture propagation, and proppant migration in hydraulic fracturing.

1. Introduction

In-depth comprehension of the initiation, expansion, and proppant transport of fractures during the fracturing process is of great importance for the development and production of oil and gas fields. This understanding helps in optimizing fracturing operation parameters, improving the effectiveness of fracture networks and the efficiency of oil and gas extraction. The advancements in computational and experimental techniques provide new insights into the study of rock fracturing and proppant transport.

This work discusses the latest developments in the theory and technology of unconventional oil and gas reservoir development, including the analysis of the mechanical properties and brittleness characteristics of shale under low-temperature fluid, the proppant transport mechanism in fractures, the kerogen mechanical properties, the impact of non-planar fracture structures on reservoir fracturing, the correlation analysis between stress evolution and fracture characteristics during the fracturing process, the fracture initiation characteristics of elliptical wellbores, and the fluid pressure on the initiation and expansion of hydraulic fractures.

2. Fracture propagation and rock mechanics during hydraulic fracturing

The simulation of fracture initiation and expansion in rocks is a critical step in the development of unconventional oil and gas reservoirs. This is because it can fundamentally describe the process of fracture formation, demonstrating the morphology, expansion and distribution of fractures during the fracturing process. Recent investigations indicate that fracture initiation in the vicinity of wellbore exhibits an anisotropic shape. A dual strength and toughness criterion could be used to study the fracture initiation characteristics from oval wellbores subject to a far-field stress field. A critical value of the ellipse

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*Corresponding author.
E-mail address: liaoqz@cup.edu.cn (Q. Liao) ; bin.wang@cup.edu.cn (B. Wang) ; cx_chenxiang@163.com (X. Chen) ; tanpeng09jy@163.com (P. Tan) .

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shape factor, defined as the length ratio between the differences over the summation of the two semi-axes, can be derived under the condition that the fracture nucleation site is random on the oval circumference and the corresponding initiation pressure is dependent on the remote mean stress and the tensile strength. If the length of the semi-minor axis is specified, the critical ellipse shape factor at a given stress field can be used to divide the borehole shapes into two classes based on the fracture nucleation site. For small-size wellbores, the initiation pressure is dominated by fracture toughness, and for large-size wellbores, the initiation pressure is dominated by tensile strength. The initiation location is affected by both the stress state and wellbore shape, and multiple fractures are easier to initiate in the presence of a noncircular wellbore and tend to develop into an "X" shape (Zhou et al., 2022).

By integrating reservoir geological structure and characterizing the developed bedding fractures from a mechanical perspective, one can elucidate the mechanism of hydraulic fracture propagation in laminated shale reservoirs, providing assistance in understanding the propagation of hydraulic fractures and optimizing construction parameters (Sheng et al., 2022). Meanwhile, it is found that the computational efficiency can be 20-25 times faster than the traditional numerical algorithm in computing the partial derivatives of the kernel functions, based on the analytical integration and differential expressions of the basic solution of the displacement discontinuity method using triangular elements. This approach also accommodates more general three-dimensional closed-contour boundary problems, such as cavities and excavation tunnels, for crack propagation in fracture-vug type composite media (Li and Zhang, 2023).

The pressurization of fluid within fractures has a significant impact on the initiation and propagation process of hydraulic fractures. Under the condition of constant flow injection, a lower injection rate reduces the breakdown strength by activating shear fractures in a larger area infiltrated by the fluid. Simultaneously, a conceptual model characterizing the fracturing process under constant pressure based on wave-like theory can be established to quantify the correlation between the constant pressure fracturing process and the cyclic variation of pumping parameters (Zhang et al., 2023).

Mineral structure also shows great effect on fracturing pattern of interlayer and oil layer of Lucaogou formation rock. On a microscopic scale, the physical, mechanical and mineral anisotropy of the two were compared, and uniaxial compression tests can be conducted with real-time micro-CT scanning. Subsequently, by performing the mineral analysis on the damaged section of the tested sample, it is revealed that the ankerite only exists in the oil layer. The fracture pattern is influenced not only by stress conditions but also by microstructure, mineral composition and distribution (Sun et al., 2023).

A discrimination method for determining the propagation behavior of hydraulic fractures in layered unconventional reservoir can offer guidance for analyzing complex hydraulic fracturing networks in layered formations. The relevant achievements can be summarized into four aspects: testing of rock mechanical properties and hydraulic fracturing experiments, expansion behavior of hydraulic fractures after encountering structural planes, the influence of weak bedding plane properties on the penetration behavior of hydraulic fractures, and the correlation between hydraulic fracture propagation and geostress evolution characteristics (Zheng et al., 2022).

Low-temperature experiments and modeling could be used to study how liquid nitrogen affects shale's cracking behavior, providing insights into stimulating shale reservoirs with cryogenic fluids. Using a fully coupled thermo-elastic model incorporating the strain-based isotropic damage theory, it is uncovered that the cooling-dominated cracking behaviors and some critical conditions for cryogenic fluid shock through three typical cases, where the reservoir contains a wellbore, a primary fracture and preexisting natural fractures, respectively. A fully coupled thermo-hydro-mechanical-damage model considering ice-water phase change helps to investigate the trans-scale progressive cracking process of gas-enriched or water-saturated shale reservoirs stimulated by liquid nitrogen injection (Han et al., 2024).

3. Fluid flow and proppant migration during hydraulic fracturing

The research of fluid flow within fractures during hydraulic fracturing revealed that the practice of cyclic fluid injection can lower reservoir breakdown pressures, thereby reducing the potential seismic risks associated with hydraulic stimulation. Also, in deeper formations, thermal effects have emerged as a crucial factor influencing the properties of fracturing fluid (Jia et al., 2021). Under varying subsurface temperatures, the mechanical properties of kerogen evolve in two stages with thermal maturity: the oil-generation wet-gas stage and the dry-gas stage. The mechanical parameters increase slowly during the first stage, whereas they increase rapidly during the dry gas stage. The change in mechanical properties of kerogen with thermal maturity is mainly controlled by variations in chemical structures (Wang et al., 2022).

Rough fracture network modeling provides more accurate simulations of fluid flow in fractured reservoirs compared to conventional methods, as it accounts for the impact of fracture roughness on fracturing and seepage processes. The results of application in fracturing and seepage simulation show that the roughness of natural and artificial fractures has a significant impact on their fracturing and seepage during reservoir transformation. Compared with reservoir transformation simulation using conventional discrete fracture network modeling techniques, using rough discrete fracture network modeling techniques for reservoir fracturing and seepage simulation can better reflect the fracturing and seepage processes of reservoirs and obtain more accurate simulation prediction results (Wu et al., 2024).

The transportation of proppants in the fracture network during hydraulic fracturing is significantly influenced by multiple factors, including the viscosity of the fracturing fluid, the angle of the fractures, the width of the fractures, and the size of the proppants. For the three-dimensional reconstruction of rough fracture surfaces, casting method provides a way to observe the characteristics of rough fractures (Huang et al., 2024). Moreover, a large-scale proppant transport experimental setup can be developed to monitor the influence of fracture inclination, fracture width, and fracturing fluid viscosity on proppant transport and positioning in coarse fractures. Simultaneously, with the progression of computational capabilities, integrated computational fluid dynamics and discrete element method can be employed to simulate the movement of micro-proppants in rough fractures (Zhou et al., 2023).

Higher fracturing fluid viscosity, even for supercritical CO_2, enhances proppant carrying capacity, with larger proppant size leading to better flow conductivity. Optimal proppant choice depends on fracture geometry and closure stress to maximize flow while preventing proppant crushing. The fine-grained proppant is not obviously broken after pressurization, while the coarse-grained proppant is obviously broken under high closed pressure, thus it is not suitable for cracks with large inclination angles. Under the same closing pressure, the smaller the crack inclination, the deeper the proppant is embedded, the fractal dimension and roughness of the crack surface increase, and the flow conductivity is also stronger. In addition, the Reynolds number and Gravity number are the dominant factor that affecting the sediment and collaging patterns. Surface roughness intensifies the particle sediment and clogging over a rough fracture. These findings provide a better understanding of transport behaviors of micro-particle over rough fractures in subsurface flow processes (Zheng et al., 2024).

4. Conclusions

This study underscores the importance of fracture network modeling techniques, fluid pressure, rock mechanics, and fracture propagation and proppant migration in hydraulic fracturing. The initiation and expansion of fractures in rocks are fundamental to the stimulation of unconventional oil and gas reservoirs. Integrating reservoir geological structure helps to characterize the developed bedding fractures from a mechanical perspective. The pressurization of fluid within fractures significantly impacts the initiation and propagation process of hydraulic fractures. A lower injection rate reduces the breakdown strength by activating shear fractures in a larger area infiltrated by the fluid. The use of rough discrete fracture network modeling techniques can provide more accurate simulation prediction results. The practice of cyclic fluid injection can lower reservoir breakdown pressures, reducing potential seismic risks. The transportation of proppants is influenced by multiple factors, including the viscosity of the fracturing fluid, the angle and width of the fractures, and the size of the proppants. In sum, the fracture propagation and proppant migration should be paid special attention to in future research on reservoir stimulation.

Conflict of interest

The authors declare no competing interest.

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