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Perspective

Recent advancements and practices of fracturing technology in continental shale reservoirs

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Abstract:
In continental shale reservoirs, the complex construction, limited fracture height and small stimulated volumes result in poor adaptability and low recovery efficiency when traditional shale fracturing techniques are used. This work introduces the recent improvements in fracturing technology developed for continental shale reservoirs and highlights the challenges and technological innovations required to enhance oil recovery. Lately, several innovative fracturing techniques have been developed that are suitable for the efficient development of continental shale reservoirs. These new proposed fracturing techniques primarily enhance the recovery of continental shale reservoirs by optimizing fracture creation and expansion, improving permeability, or increasing the stimulated reservoir volume. Several practical applications of these technologies in complex fault shale reservoirs, matrix-dominated shale reservoirs and complex structural shale reservoirs have demonstrated significant improvements in oil production. However, further research is needed with respect to determining the technical parameter boundaries for fracturing in different depressions and reducing costs, in order to refine these technologies and advance the efficient development of continental shale resources.

1. Introduction

Fracturing in continental shale reservoirs faces many challenges such as complex construction, limited fracture height expansion and small stimulated volumes (Ding et al., 2016; Wang et al., 2023). Therefore, conventional fracturing technologies struggle to efficiently exploit these reservoirs. Since these challenges were recognized, extensive technological research has been undertaken. Based on a deeper understanding of geological and reservoir dynamics, efforts have focused on upgrading and refining existing fracturing techniques, bolstering theoretical research on shale fracturing and developing cubic fracturing methodologies. These endeavors have led to significant breakthroughs in fracturing technologies tailored for continental shale reservoirs. Furthermore, field fracturing operations have demonstrated marked improvements in stimulated volume compared to similar reservoirs globally (Chen et al., 2021; Yang et al., 2022a; Guo et al., 2024). This progress underscores the success of relevant fracturing technology systems in enhancing the fracturing and development capabilities of continental shale reservoirs (Gomaa et al., 2014; Sheng et al., 2024).

2. Fracturing technology

The pressure gradient required for infiltration exceeds 50 MPa/m of the continental shale matrix. Poor fluid flowability, high compressive strength and strong plasticity are all unfavorable for fracture initiation and expansion (Zhao et al., 2018; Hui et al., 2022; Yang et al., 2022b). Recognizing these challenges, enhancements were introduced with the aim of achieving the “well control” of reserves, which has spurred the development of various technologies including low-concentration pre-acid fracturing, pre-CO_2 fracturing, fracture network fracturing, controllable cross-layer fracturing, and subdivision cutting fracturing, among others. These efforts have realized an advanced fracturing technology for continental shale reservoirs, marking a significant breakthrough in shale fracturing and development.

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2.1 Low-concentration pre-acid fracturing

Pre-acid fracturing involves injecting acid into the reservoir at pressures exceeding the fracture threshold, which causes a portion of the acid to lead the fracture propagation, with the remainder diffusing to either side of the fracture surface. The acid is subsequently separated from the fracturing fluid using an isolation fluid, paving the way for hydraulic fracturing. Adding low-concentration acid to the pre-fracturing fluid can increase permeability, decrease the fracturing pressures and augment the fracturing efficacy (Pournik et al., 2019). Empirical evidence from the continental shale reservoir underscores the efficacy of low-concentration acid in fostering wormhole formation in mudstone. Meanwhile, pre-acid fracturing also mitigates construction pressures. In reservoirs laden with high ash content, this technique can slash fracture pressures by 18-23 MPa. Furthermore, employing multi-stage acid treatments can widen fractures and enhance proppant penetration into fractures.

2.2 Pre-CO_2 fracturing

Utilizing liquid CO_2 as the pre-fracturing fluid and blending it with other water-based fracturing fluids for stimulation can facilitate reservoir transition from plasticity to brittleness, increase the number of micro-fractures, decrease the principal stress difference, and notably make the fracture network more intricate (Song et al., 2024). From CO_2 injection, co-injection and pre-CO_2 fracturing tests (Zhang et al., 2022), it was found that pre-CO_2 fracturing brings the advantage of enhancing the stimulation volume. Under equivalent fracturing parameters, pre-CO_2 fracturing exhibited a 21% increase in stimulated reservoir volume compared to conventional hydraulic fracturing. The comparison of hydraulic fracturing and pre-CO_2 fracturing in the continental shale reservoir revealed that injecting a certain amount of CO_2 before the water-based fracturing fluid significantly impacts the enhancement of the fracturing stimulated volume. Other crucial parameters include CO_2 injection volume and timing, which require optimized research tailored to specific shale reservoirs. In the application to Shengli continental shale reservoirs, it was found that under a CO_2 injection volume of 5-6 t/m (single section $>$ 200 t), the stimulated volume of reservoir in the section with CO_2 injection was 1.7 times greater than that in the section without CO_2 injection, effectively enhancing the stimulation efficacy.

2.3 Fracture network fracturing

An innovative fracture network fracturing approach, termed as "self-supporting fractures-branch fractures-main fractures", can enhance fracture control reserves while refining construction and proppant pumping methodologies. As for the fracture network fracturing technology, designing the fracturing fluid injection sequence and optimizing the fracturing fluid distribution ratio among multiple fractures are crucial for enhancing the complexity of the fracture network and increasing the oil supply capacity. Alternating pulse pump injections enable the formation of cluster-supported, highly conductive fractures. By alternately injecting "pure liquid" and "mortar", fibers coalesce into clusters, allowing the fracturing fluid to create and simultaneously fill fractures, yielding highly conductive fractures. Thus, the conductivity of the main fracture can be augmented by 5-7 times. However, to further enhance oil recovery by the fracture network fracturing technology, the technical parameters should be optimized. To effectively utilize the fracturing effects in primary and branch fractures, it is necessary to develop optimization methods for multi-stage fracture diversion, where the reasonable technical parameters, such as displacement, liquid volume, and proppant injection methods, can be optimized. Compared to conventional fracturing techniques, field trials demonstrated a 1.54-fold increase in the post-fracturing oil supply capacity.

2.4 Controllable cross-layer fracturing

Due to the geological features of high-angle and overpressure fractures in continental shale reservoirs, it is necessary to achieve longitudinally controllable fracturing techniques during the fracturing process. It was found that the controllable cross-layer fracturing technique, characterized by high displacement and the alternating injection of variable viscosity fluids, can effectively achieve cross-layer fracture propagation (Wu et al., 2020). For the cross-layer fracturing technique, the most important aspect is the alternating injection of fracturing fluids with different viscosities at various stages of fracturing, to promote the development of multi-stage cross-layer fractures within laminated gray shale formations. Through refined fracturing strategies that regulate perforation density, implement short-term high displacement pressure suppression and facilitate gel expansion to control fracture height, controllable cross-layer fracturing can successfully demonstrate the cross-layer expansion of enriched bedding shale. Field trials have demonstrated the doubling of shear failure, with the equivalent construction displacement increasing from 8 to 16 m^3/min, and stimulated reservoir volume (SRV) increasing by 64%. A single cluster displacement exceeding 3 m^3/min, coupled with a net pressure surpassing 8 MPa, has proven effective sin penetrating layers and expanding fracture height.

2.5 Subdivision-cutting fracturing

The subdivision-cutting fracturing technology, which reduces the spacing between clusters and increases the number of fracturing clusters, is an important strategy to achieve the efficient development of shale reservoirs (Deng et al., 2021). In subdivision-cutting fracturing, the small distance between fractures leads to significant stress interference during fracturing, which can have both beneficial and detrimental effects on production. Therefore, optimizing the fracture spacing is crucial in subdivision-cutting fracturing. The application of subdivision-cutting fracturing technology in shale reservoirs has shown that smaller cluster spacing intensifies fracture interference. With increased spacing between clusters, the interference diminishes, along with a reduction in fracture pressure. On the other hand, stress interference induced by subdivision-cutting fracturing can prompt stress turning. This phenomenon may lead to fracture redirection or the initiation of natural micro-fracture opening and sliding, thereby enhancing the likelihood of fracture network formation (Shanshan et al., 2021). Meanwhile, it inevitably affects the extension of the primary fracture. Consequently, subdivision-cutting fracturing demands the comprehensive assessment of factors such as SRV, fracture network width and fracture complexity index. As cluster spacing decreases, SRV and fracture network width will gradually stabilize, obviating the need for additional clusters. Balancing production and operational costs, an optimal cluster spacing of 7 to 13 m is deemed suitable for continental shale reservoirs.

3. Practical aspects

3.1 Complex fault block shale oil reservoirs

Complex fault block shale oil reservoirs exhibit features such as complex structure, developed faults and fractures, and multiple oil layers. At present, the key research focus is on how to smoothly add sand during the hydraulic fracturing of such reservoirs and increase the SRV. Extensive hydraulic fracturing practices indicate that cubic fracturing, involving "local stress interference with CO_2 + multiple-stage fracturing with fewer clusters + fixed horizontal plane perforation + viscosity-microfine sand matching", can achieve the efficient development of such reservoirs. One typical well group situated in the complex fault block shale oil reservoirs of Shengli marks the inaugural implementation of cubic fracturing in continental shale reservoirs. The development results of this typical well group are highly promising, highlighting the significant progress made in the field of multi-well collaborative cubic fracturing within the well group.

3.2 Matrix-dominated shale oil reservoirs

Matrix-dominated shale reservoirs often exhibit significant differences in horizontal stresses and are characterized by low maturity, high clay content and high oil viscosity. Hydraulic fracturing in such reservoirs faces many challenges, such as difficulty in extending fractures in high-stress areas and complicating the fracture network. Due to the large differences in horizontal stresses, the complexity of fractures is limited. Additionally, shale layers are well-developed, making it difficult for fractures to penetrate through them. Controllable cross-layer fracturing technology strengthens the complexity of the fracture network through multi-stage temporary blocking, facilitating the efficient development of such reservoirs. Taking a typical matrix-dominated shale reservoir in Shengli as an example, the controllable cross-layer fracturing technology is employed in four wells. Additionally, this well group has seen significant advancements in this technology, further underscoring the success of the project.

3.3 Complex structural shale oil reservoirs

Complex structural shale reservoirs often exhibit features of intricate structures, significant elevation differences, large formation dip angles, and substantial variations in organic matter maturity. The efficient development of such reservoirs can be facilitated by utilizing the subdivision-cutting fracturing technology. Fracturing activities in such reservoirs primarily adhere to the principles of this technology, continually pushing the boundaries of cluster spacing, the shortening of fracture lengths, and intensifying volume fracturing. In field case studies, subdivision cutting fracturing technology has shown promising results in enhancing oil recovery in complex structured shale reservoirs.

4. Conclusion and Outlook

The fracturing technology for continental shale oil horizontal wells has been gradually improved in recent years, while further research is needed to determine the technical parameter boundaries for fracturing in different depressions, enhance the key technology system for cubic fracturing, and further reduce the engineering costs.

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Conflict of interest

The authors declare no competing interest.

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