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A Comprehensive Review of Hydraulic Fracturing Techniques in Shale Gas Production

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ABSTRACT

Shale gas has emerged as a significant source of natural gas due to advancements in hydraulic fracturing and horizontal drilling technologies. This extraction method has facilitated drilling and production activities in regions previously untouched by oil and gas development. Hydraulic fracturing, a well-stimulation technique suitable for low and moderate-permeability reservoirs, relies on the successful drilling of horizontal wells and the creation of multiple hydraulic fractures to ensure economic viability. While shale gas presents significant energy production opportunities, concerns have been raised regarding its environmental impact. To mitigate these risks and determine the most effective approach for shale gas extraction, alternative fracturing technologies are being investigated. Notably, a considerable number of perforation clusters in shale gas horizontal wells do not contribute to production, highlighting the potential for refracturing. Therefore, a comprehensive analysis is required to evaluate the performance of hydraulic fracturing and alternative fracturing technologies in shale gas wells, considering factors such as cost-effectiveness, environmental impact, and gas extraction efficiency. This article aims to evaluate the hydraulic fracturing technology's capability to enhance gas recovery in shale gas formations as well as its environmental implications. The focus of this research is primarily on the hydraulic fracturing technique employed in shale gas development, its production capability, and associated environmental concerns. Through a systematic evaluation, this study provided valuable insights into the potential of hydraulic fracturing in maximizing gas recovery while addressing environmental challenges in shale gas formations.

KEYWORDS: Shale gas, hydraulic fracturing, fracturing technology, horizontal drilling, production enhancement.

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1 | INTRODUCTION

Shale gas, a previously challenging natural gas resource to extract, has witnessed a transformative shift with the advent of hydraulic fracturing and horizontal drilling technologies [1]. These innovations have enabled the exploitation of shale gas reservoirs, unlocking vast reserves of natural gas in regions with limited prior oil and gas development activities [2]. Hydraulic fracturing, a well-stimulation technique tailored for low and moderate-permeability reservoirs, relies on drilling horizontal wells and creating multiple hydraulic fractures to achieve economic viability [3].

Despite the extensive development of shale gas reservoirs worldwide facilitated by horizontal well fracturing technology, the industry faces significant challenges such as production attenuation and rapid decline of oil and gas wells [4]. The volatile nature of international oil prices and the comparatively low economic benefits associated with new drilling have compelled operators to seek more cost-effective stimulation techniques. Consequently, the focus has shifted towards maximizing production in mature wells through horizontal well refracturing - an economically viable and efficient alternative to traditional drilling methods.

Although shale gas presents promising energy prospects, concerns have been raised regarding the environmental impact of hydraulic fracturing. To address these concerns and identify the most suitable approaches for shale gas extraction, researchers are investigating alternative fracturing technologies. Notably, statistics indicate that a substantial percentage of perforation clusters in shale gas horizontal wells do not contribute to production, highlighting the potential for refracturing [5]. Consequently, a comprehensive analysis is necessary to evaluate the performance of hydraulic fracturing and alternative fracturing technologies in shale gas wells, considering factors such as cost-effectiveness, environmental impact, and gas extraction efficiency.

In this context, this article aims to evaluate the potential of hydraulic fracturing technology

2 | MATERIALS AND METHOD

This review paper focused on hydraulic fracturing technology in shale gas formation and aims to provide a comprehensive evaluation of the topic. The research design employed in this study is a systematic review, which involves synthesizing and critically analyzing multiple studies to address the research question. This design was appropriate as it allowed for a thorough examination of hydraulic fracturing technology and facilitated the identification of knowledge gaps and areas for future research.

The methodology used in this review consisted of five distinct steps: reviewing previous research, inclusion screening, evaluating the value of original research, data extraction, and data synthesis. Reviewing existing literature provided a comprehensive understanding of the current knowledge on the subject, and allowed for the assessment of the quality and validity of previous studies. Inclusion screening ensured that only high-quality and relevant studies were included in the review, based on specific criteria related to the research study. Evaluating the value of original research involved assessing the quality, reliability, and relevance of the studies to the review research study, contributing to a comprehensive analysis of the available literature. Data extraction involved systematically gathering and recording relevant data from primary research studies, including fracturing techniques details, data collection and analysis methods, and findings. Finally, data synthesis entailed analyzing and synthesizing the collected data to identify patterns, trends, and relationships relevant to the research topic, allowing for the development of a comprehensive and coherent understanding of hydraulic fracturing in shale gas development.

2.1 Fracturing Technology

Hydraulic fracturing plays a critical role in extracting hydrocarbons from unconventional reservoirs. Factors like well type, reservoir properties, and fracturing fluid impact its effectiveness. Techniques such as simultaneous fracturing, multi-fracture network, stage fracturing, and re-fracturing enhance output and recovery, making them valuable tools for the oil and gas industry.

2.2 Simultaneous Fracturing

Simultaneous fracturing is a hydraulic fracturing technique used to fracture multiple zones or layers of a wellbore at the same time. This technique was developed to improve the efficiency and efficacy of hydraulic fracturing in low-permeability reservoirs. Simultaneous fracturing allows for more efficient and effective fracturing since fractures can be formed concurrently and are less likely to seal before they can fully propagate. Recent studies have shown that simultaneous fracturing is faster and cheaper than zipper-fractured completions when treatment rates per well were equivalent [6]. Halliburton's simul-frac operations have been found to achieve over double the gains in lateral footage, in less time, compared to zipper-frac operations [7].

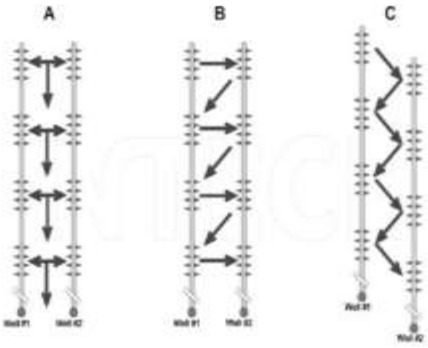

Fig. 1: Simultaneous Fracturing (A), Sequential Fracturing (Zipper-Frac) (B), and Modified Zipper-Frac (C) [8]

Simultaneous multiple-fracture treatments in horizontal wellbores are being used to economically develop unconventional resources in shale reservoirs [9]. To study the mechanism of multiple fracture initiation in unconventional reservoirs, true tri-axial hydraulic fracturing laboratory experiments play an essential role. However, uneven propagation of multiple fractures existed and even some fractures fail to initiate. Limited-entry fracturing method (LEF) using perforated wellbores and a limited number of perforations is being widely applied to further improve the efficiency of fracturing multiple clusters. To achieve extremely high perforation friction in unconventional reservoirs, Somanchi et. al. [10] have recently developed extreme limited-entry fracturing methods (XLEF).

According to Li et. al. [11], multiple fracture simultaneous propagations in the extremely limited-entry perforated wellbore have been proven. The study investigated the multiple fracture simultaneous propagations in the XLEF perforated wellbore based on the true tri-axial fracturing experiments. Critical factors of horizontal stress difference (HSD), the number of perforation clusters, helical/in-plane perforated method, number of perforations per cluster, and fracturing fluid flow rate were investigated in detail. The injection pressure curve, fracture geometries on the rock sample, and three-dimensional fracture geometries after construction were analyzed in detail. Based on these data, the optimal parameters for obtaining high perforation cluster effectiveness and the possibility of longitudinal/axial fractures or transverse fractures have been fully discussed [11].

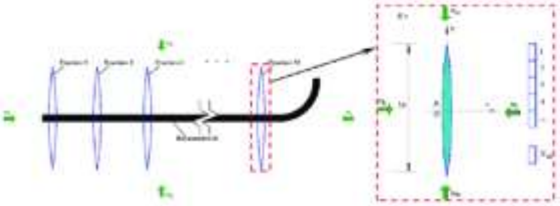

Fig. 2: Simultaneous Expansion of Multiple Fractures in a Horizontal Well [12]

The study provides a meaningful perspective for the multiple fracture propagation in the perforated wellbore during XLEF, which could help field engineers to further understand the fracture morphology and optimize the corresponding fracturing parameters for better stimulation results in the subsurface [11].

2.3 Risk and Challenges Affecting Simultaneous Fracturing

Simultaneous fracturing enhances fracture complexity, conductivity, and extends the fairway [13, 14], but the reasons for its success are not fully understood [15]. Challenges include increased pressure, equipment coordination, and chemical management. Thorough research, planning, and risk assessment are essential for safe and successful operations. Although it offers benefits like increased hydrocarbon output and efficiency, drawbacks include complexity, wellbore instability, and limited control over fractures. Tailoring treatments to specific reservoir conditions is challenging. Each well and reservoir should be approached individually to determine the appropriateness of simultaneous fracturing.

2.4 Multi-Fracture Network Fracturing

Multi-fracture network fracturing, which involves creating multiple fractures in a rock formation, has become a popular method for stimulating unconventional resources such as tight oil and shale gas using multi-cluster fracturing technology in horizontal wells [16, 17]. This technique involves injecting high-pressure fracturing fluid to create multiple transverse fractures, significantly improving the contact area in the pay zone [18, 19]. To reduce costs and increase production capacity, the standard practice is to perforate multiple clusters in a single fracturing segment and make multiple fractures propagate simultaneously [20, 21, 22]. However, recent downhole monitoring data has shown that multiple fractures often fail to propagate uniformly and sometimes even fail to initiate [23, 24, 25].

To address these issues, various techniques have been proposed, such as increasing the number of perforation clusters, optimizing cluster spacing and orientation, and adjusting the pumping rate and fluid viscosity [11]. Advanced modeling and simulation tools, such as true tri-axial fracturing experiments and CT scanning, are also being used to better understand fracture initiation and propagation in heterogeneous formations. By improving our understanding of the underlying physics and mechanics of multi-cluster fracturing, we can optimize this stimulation technology and increase its effectiveness in producing hydrocarbons from unconventional reservoirs.

A recent study by Zhao et. al. [26] investigated the characteristics of hydraulic fracture networks in full-diameter shale cores using X-ray CT scanning. The study discovered three common types of hydraulic fracture networks and examined the effect of pore pressure and slippage on fracture network permeability. The results showed that hydraulic fractures completely penetrated the shale samples in the direction of gas seepage and that fracture conductivity improved as fracture width and volume increased. In contrast to the Klinkenberg coefficient, the study found that absolute permeability was positively correlated with the number of effective seepage channels in hydraulic fractures and the number of hydraulic fractures.

Another recent study conducted by Li et. al., [11], investigated the multi-fracture morphology during Temporary Plugging and Diverting Fracturing (TPDF) through true tri-axial fracturing experiments and CT scanning. They analyzed critical parameters such as fracture spacing, number of perforation clusters, the viscosity of fracturing fluid, and the in-situ stress, and quantitatively analyzed the fracture geometry before and after diversion based on two-dimensional CT slices and three-dimensional reconstruction methods.

The perforation cluster spacing by Li et. al., [11], compared 2D CT slices based on Tests 1-3 with different fracture spacings and found that regardless of the fracture spacing, only one hydraulic fracture was created in the initial fracturing stage (IFS). However, multiple perforation clusters could simultaneously initiate after diversion fracturing stage (DFS), but the propagation behavior of diverted fractures was significantly different due to the fracture spacing. With smaller fracture spacing, the complexity of the fracture network was higher after the DFS. More shear fractures between hydraulic fractures could be generated among close-spaced fractures, while only a few bifurcated fractures were generated among loosely-spaced fractures.

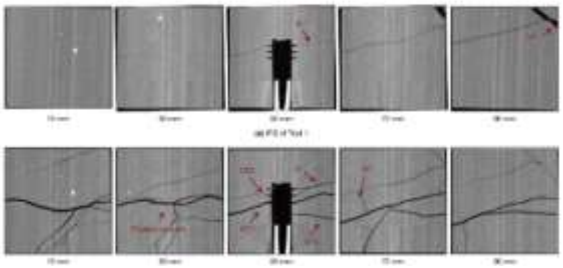

Fig. 3: CT scanning after IFS and DFS in Test 1 [11]

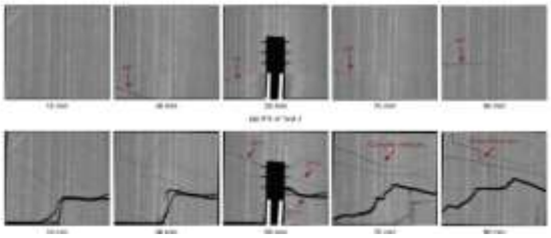

Fig. 4: CT scanning after IFS and DFS in Test 2 [11]

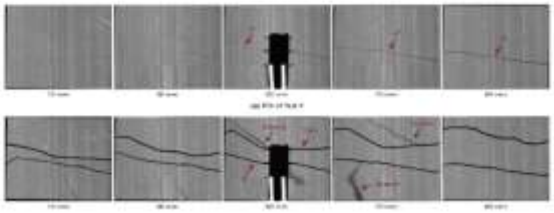

Fig. 5: CT scanning after IFS and DFS in Test 3 [11]

Li et. al., [11], also looked at the effect of fracturing fluid viscosity on fracture performance. Usually, low-viscosity fluids produce lower friction, while high-viscosity fluids can better carry proppants or diverters. Tests were conducted using slickwater with different viscosities and cross-linked HPG fracturing fluid. The pressure curves showed that the high-viscosity fracturing fluid had higher peak injection pressure and propagation pressure in the initial fracture stage (IFS) and created two fractures at the side position. Meanwhile, the low-viscosity fluid only created one fracture in IFS. After the diversion fracture stage (DFS), all perforation clusters in the wellbore can be initiated regardless of the fluid viscosity.

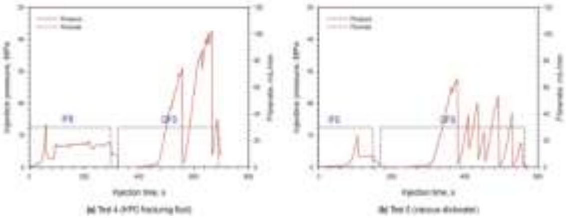

Fig. 6: Injection pressure under different fluid viscosity [11]

The sample using high-viscosity fluid had a higher complexity of fracture network than that using low-viscosity fluid due to the activation of more natural fractures and better carrying of diverters into the fractures. Furthermore, CT scanning showed that the initial fracture width formed by high-viscosity fluid was wider and the diverted fractures within the fracture were more complex. However, the fracture width formed by low-viscosity fluid was narrow and the diverters can only accumulate in the wellbore without forming complex diverted fractures within the fracture.

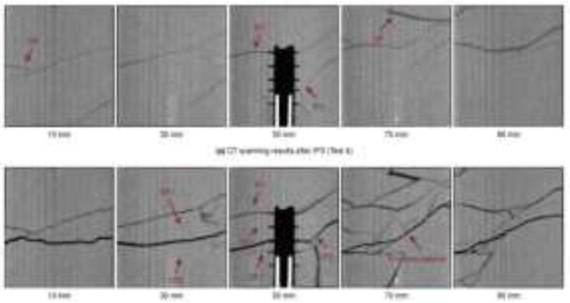

Fig. 7: CT scanning after IFS and DFS [11]

The study concluded that the influence of fracturing fluid viscosity mainly lies in the injection pressure and fracture morphology. (Fig. 6, Fig. 7).

Overall, Li et. al., [11], found that natural fractures and stress interference were the primary reasons for reducing the Perforation Cluster Effectiveness (PCE) during IFS in shale reservoirs. However, PCE can be significantly increased after diversion. The PCE in the IFS was only 26.92%, but it improved to 88.86% after the DFS. Natural fractures and beddings increased the complexity of the fracture network, but they limited the propagation of fracture height. Additionally, natural fractures limited the propagation of fractures far-field, leading to the merger of multiple hydraulic fractures.

Increasing the viscosity of the injection fluid and selecting perforation clusters in the lower in-situ stress zone greatly improved the PCE in IFS. The study also revealed four types of temporary plugging behavior in shale, namely, plugging the natural fracture in the wellbore, plugging the previous hydraulic fractures, plugging the fracture tip, and plugging the bedding. These four plugging behaviors can be controlled by adjusting the diverter recipe and diverter injection time.

In summary, the study provided valuable insights into the initiation and propagation of multi-cluster fractures in horizontal wells. The experimental results revealed the impact of various factors on PCE, fracture complexity, and temporary plugging behavior. The findings can be used to optimize multi-cluster fracturing designs in shale reservoirs.

After considering the data and results presented, it can be concluded that multi-fracture network fracturing is a highly effective method for enhancing oil and gas production in unconventional reservoirs. However, it is important to note that the decision to implement this technology should not be taken lightly, as there are both economic and operational risks to consider. Careful consideration of the costs and potential risks associated with multi-fracture network fracturing is necessary to ensure that the benefits of increased production are balanced against potential negative impacts.

2.5 Factors Affecting Multi-Fracture Network Fracturing

Multi-fracture network fracturing is a technique that depends on various factors for its success. These factors are geological, engineering, and operational. Geological factors such as rock type, mineralogy, and stress regime can influence multi-fracture network fracturing. The presence of natural fractures or faults in the rock can significantly enhance the efficacy of this technique. Engineering factors such as the design of the fracturing fluid, the positioning of the fractures, and the usage of proppant can also affect multi-fracture network fracturing. The viscosity of the fracturing fluid can have a significant impact on the complexity of fracture extension. Proper spacing and orientation of the fractures are required to optimize the surface area capable of producing hydrocarbons. Proppant can aid in keeping the fractures open and increasing the technique's efficiency. Operational factors such as the rate and pressure at which the fracturing fluids are injected, the duration of the fracturing treatment, and fluid flow back must be carefully addressed in the design and execution of a multi-fracture network fracturing treatment.

2.6 Stage Fracturing

Stage fracturing, also known as multi-stage fracturing, is a widely used technique in the oil and gas industry to increase hydrocarbon production from unconventional sources like shale and tight sands. It involves fracturing the well in multiple stages, typically 10 to 15, to ensure optimal coverage of the reservoir. The number of stages required is dependent on the lateral length of the well [27]. Proppant and fracturing fluids are pumped into the wellbore at each stage to create cracks in the surrounding rock, with the proppant keeping the cracks open.

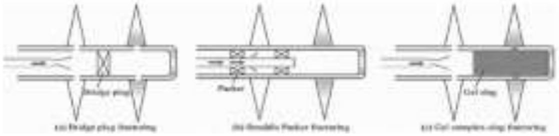

Fig. 8: Horizontal Wells' Staged Fracturing Technique [28]

There are three common staged fracturing methods as shown in Fig. 8: bridge plug fracturing, through coiled tubing fracturing with straddle packer, and gel complex-slug fracturing. Achieving multi-stage fracturing in a horizontal well requires including several perforation clusters in each stage to create a fracture network with a similar stimulated reservoir volume (SRV). However, it can be challenging to stimulate all the perforations equally due to different numbers of openings in each cluster.

Stage fracturing offers advantages such as increased production, better control, improved efficiency, enhanced reservoir understanding through monitoring, and reduced operation time. A study by Yang et al. [29] verified the accuracy of a model by comparing its solutions to production profiles in a horizontal well. The results showed a high degree of consistency, demonstrating the initiation of fractures at different perforation clusters as depicted in Fig. 9. The result displays the bottom-hole pressures and the corresponding total pump rates required to initiate fractures at three perforation clusters. Fractures initiate at the horizontal heel end and finger first, and then the cluster's fracture is initiated at cluster no. 2. Despite the fluid acceptance rates shown in Fig. 10, not all perforations are active.

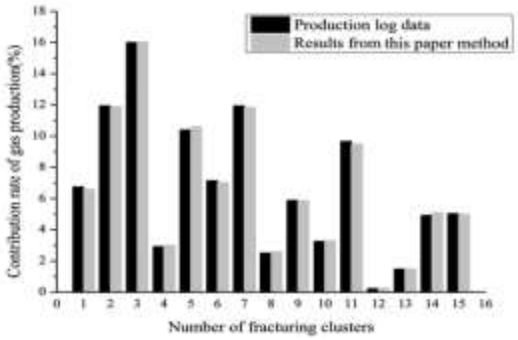

Fig. 9: Comparison of Production Profiles for Horizontal Well of MG121 [29]

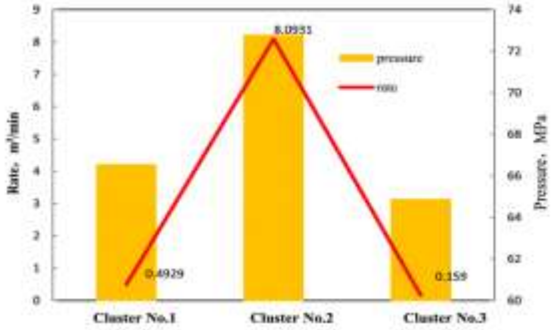

Fig. 10: Fracture Initiating Pressures and Pumping Rates at Each Cluster [29]

To evenly stimulate the reservoir between each perforation cluster, adjusting the perforation parameters and simulating the SRV using a Discrete Fracture Network (DFN) fracture model is necessary. This approach allows for even production rates across the clusters.

While stage fracturing has proven effective, it has drawbacks. It requires careful planning and execution and can be costly and environmentally challenging due to the large volumes of water involved.

2.7 Factors Affecting Stage Fracturing

The success of stage fracturing treatment depends on various factors, including reservoir properties, fracturing fluids and proppants, wellbore geometry, stress and in-situ stress, stimulation design, environmental factors, and production rate. Understanding these variables is critical to achieving the target production rate and improving treatment design. Further research is needed to gain a better understanding of the interaction and impact of these factors on the stage fracturing process.

2.8 Re-Fracturing

Re-fracturing is a cost-effective process that involves injecting fluids and proppant into an existing fractured well to enhance fracture size and quantity, increasing the contact area with the reservoir and improving hydrocarbon flow. It is commonly used on mature wells that have experienced a decline in production, particularly in unconventional reservoirs like shale gas and tight oil deposits. Re-fracturing has the potential to extend the productive life of these reservoirs by up to 20-30 years and reduce variability [30].

Studies have shown that re-fracturing can increase the net present value (NPV) of reservoirs by an average of 60% [31].

Fig. 11: After Hydraulic Fracturing Stimulation and Fracture Network, with Extra Complicated Fracture Network Formed [30].

Over 600 shale gas wells have undergone re-fracturing, resulting in production rates close to 90% of the initial production, with reduced decline rates [32]. Wang et. al. [33] simulated refracturing performance across five cases.

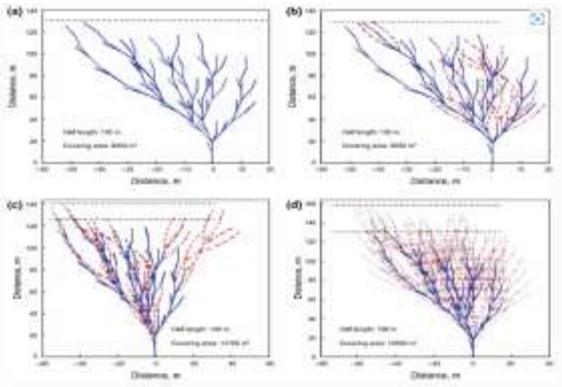

Fig. 12: Fractal Fracture Geometry for Simulation of Re-Fracturing [33]

Fig. 12 illustrates the changes in fracture geometry resulting from refracturing, highlighting the original fractal fracture network and the SRV in (a), the extension of the fracture network and growth of SRV in (b), the improvement of both the complexity of the fracture network and the area of SRV in (c) and the enhancement of fracture conductivity and extension of fractures near the well without growing the SRV in (d).

The improvement in the fracture network can be evaluated through monitoring or fracturing engineering plans. Adjusting the simulation model can enhance fracture conductivity, increase the SRV area, and reduce decline rates, ultimately contributing to higher cumulative production. The final production rate is determined by the boundary or the area of SRV, following the theory of decline curve analysis or Rate Transient Analysis (RTA). Fig. 13 presents the results.

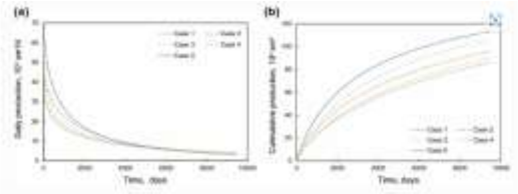

Fig. 13: The Production Rate and Total Production Simulated by Different Cases [33]

However, it is crucial to note that re-fracturing is not a one-size-fits-all solution and must be evaluated on a case-by-case basis. Environmental considerations are important, and re-fracturing should adhere to regulations and best practices to minimize any potential impact.

2.9 Current Status of Re-Fracturing Technology Development

Currently, there are primarily three types of re-fracturing technologies available:

1. Temporary plugging and diverting technology: This approach involves using a temporary plugging agent to create new fractures by diverting fracturing fluid towards unfractured areas. While it is relatively inexpensive and has a simple process, controlling the diversion process can be challenging.
2. Mechanical isolation technology: This method involves blocking perforations in the production section using a liner to create a new wellbore that is then perforated for refracturing. It offers good sealing effects but is limited by its high cost, complicated process, and difficult operation. [34]
3. Coiled tubing refracturing technology: This approach utilizes coiled tubing and double packers for multi-stage refracturing. It is mainly used in early open-hole sliding sleeve ball-casting wells in the Bakken Oilfield, as its application is limited due to specific completion structure requirements and operational difficulties. [35]

2.10 Re-Fracturing Technology Applications

Re-fracturing techniques can be categorized into three main approaches:

1. Repairing existing fractures involves removing contamination or restoring closed fractures to improve conductivity [4].
2. Opening new fractures utilizes temporary plugging agents or mechanical packing technologies to expand the fracture network around the wellbore [4].
3. Diverting fracturing leverages horizontal stress changes to create a complex fracture network and improve connectivity [4].

3 | EVALUATION OF THE VARIOUS FRACTURING TECHNOLOGIES

3.1 Simultaneous Fracturing

1. Simultaneous fracturing improves efficiency and efficacy in low-permeability reservoirs, reducing premature sealing.
2. It is faster and cheaper compared to zipper fracturing, leading to higher gains in lateral footage.
3. Enables the economic development of unconventional resources in shale reservoirs.
4. True tri-axial hydraulic fracturing experiments help understand multiple fracture initiation mechanisms.
5. Limited-entry fracturing methods enhance efficiency, and extreme limited-entry methods are used in unconventional reservoirs.

6. Optimal parameters and fracture geometries impact the effectiveness of simultaneous fracturing.
7. Relationships between injection pressure and fracture geometries have been studied.

3.2 Multi-fracture Network fracturing

1. Enhances contact area and reservoir fluid flow in unconventional resources.
2. Non-uniform fracture propagation poses a challenge that requires further understanding.
3. Techniques such as increasing perforation clusters and adjusting fluid properties optimize multi-fracture network fracturing.
4. Complex fracture networks impact fracture propagation and fluid flow.
5. Pore pressure and slippage affect fracture network permeability.
6. Fracture spacing and fluid viscosity influence fracture morphology and performance.
7. Temporary plugging and diverting fracturing techniques help optimize fracture network.

3.3 Stage fracturing

1. Enhances hydrocarbon production by increasing the effective drainage radius.
2. Allows for precise targeting of different reservoir sections.
3. Improves fluid flow management and proppant distribution for better fracture conductivity.
4. Provides insights into reservoir characteristics and behavior.
5. Offers efficient operation with limited downtime.

3.4 Re-fracturing

1. Increases well output in mature oil and gas fields, extending productive life.
2. Improves fracture network and reservoir drainage.
3. Optimization of fracture network conductivity and stimulated reservoir volume (SRV) contributes to higher cumulative production.
4. Case-by-case evaluation is necessary, considering reservoir characteristics and existing fractures.
5. Environmental considerations and adherence to regulations are essential.
6. Available re-fracturing technologies include temporary plugging and diverting, mechanical isolation, and coiled tubing refracturing.

In summary, hydraulic fracturing technologies such as simultaneous fracturing, multi-fracture network fracturing, stage fracturing, and re-fracturing offer various advantages and considerations. They improve efficiency, increase contact area, optimize production, and extend the productive life of oil and gas fields. However, careful evaluation and understanding of reservoir-specific factors are crucial for successful implementation and optimization.

4 | CONCLUSION

The following were the conclusions of the review:

1. The review findings highlight the potential of hydraulic fracturing technologies in enhancing efficiency and effectiveness in low-permeability reservoirs and exploiting unconventional resources in shale reservoirs.
2. Simultaneous fracturing has proven to be cost-effective, while multi-fracture

network fracturing requires optimization strategies for uniform fracture propagation.

3. Understanding the properties and behavior of hydraulic fracture networks is crucial for optimizing stimulation technologies and increasing hydrocarbon output from unconventional reservoirs.
4. Optimization techniques, including modifying cluster spacing, orientation, pumping rate, and fluid viscosity, are being investigated to achieve uniform fracture propagation in multi-fracture network fracturing.
5. Temporary Plugging and Diverting Fracturing (TPDF) techniques offer control over multi-cluster fracturing designs in shale reservoirs, with parameters such as fracture spacing, fluid viscosity, and in-situ stress playing a significant role in multi-fracture morphology.
6. Different approaches, such as simultaneous fracturing, multi-fracture network fracturing, stage fracturing, and re-fracturing, can be employed to boost output from unconventional reservoirs, and the selection should be based on the reservoir's specific properties.

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