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Review

Research Progress on Optimization Methods of Platform Well Fracturing in Unconventional Reservoirs

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Abstract: Unconventional reservoirs are characterized by low porosity, low permeability, and limited hydrocarbon abundance, making them economically unviable for production under natural conditions. Large-scale hydraulic fracturing has emerged as a critical technology for enabling the effective development of these resources. The three-dimensional development of platform wells employs batch drilling and batch fracturing techniques. By implementing simultaneous fracturing or zipper fracturing approaches, the process achieves well placement, fracturing, and fracture placement in a single step, thereby reducing costs and improving operational efficiency. Platform well fracturing (PWF) involves numerous parameters that require optimization, and the underlying physical processes are highly complex, presenting significant challenges to the design and control of fracturing strategies. To address these challenges, this study focuses on the following aspects: (1) identifying key parameters in PWF and reviewing prior optimization efforts that use production capacity and net present value as objective functions; (2) systematically comparing numerical simulation methods for modeling fracture propagation and simulating production performance, highlighting their role in linking fracturing parameters to objective functions; (3) evaluating the strengths and limitations of single-factor analysis, orthogonal experimental design, and intelligent automatic optimization methods, and proposing a high-dimensional intelligent optimization workflow for fracturing design; (4) examining the technological challenges of PWF and suggesting future directions for its development. This study provides valuable insights into the selection of optimization methods for PWF schemes and offers guidance for advancing the technology's development, contributing to more efficient and effective resource recovery from unconventional reservoirs.

Keywords: unconventional reservoirs; platform well fracturing; intelligent optimization; fracturing effect; development direction

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1. Introduction

Unconventional oil and gas resources have become a major focus of global energy development due to their vast potential and strategic importance. Many countries, including China, face significant challenges such as low reservoir permeability and rising demand, which necessitate advanced stimulation technologies like platform well fracturing (PWF). In China, for instance, reliance on foreign oil exceeded 70% in 2024, underscoring

the urgency of efficient domestic energy exploitation [1]. However, the country possesses substantial reserves of unconventional oil and gas, which represent crucial alternative resources [2]. These unconventional reservoirs, characterized by poor physical properties and no inherent production capacity under natural conditions, require enhanced stimulation to enable their effective development. Large-scale horizontal well staged fracturing is the primary method used for reservoir stimulation [3]. The goal of this technique is to create an extensive network of hydraulic fractures, supported by proppants, within the reservoir. However, this approach presents significant challenges. On the one hand, the high cost of operations—amounting to up to 20 million yuan per well—results from the large-scale injection of tens of thousands of cubic meters of fluid and sand. On the other hand, reservoir heterogeneity and the influence of the surrounding stress field can lead to pressure channeling, which causes well interference and ultimately reduces the production capacity of oil wells [4].

PWF employs the method of batch drilling and batch fracturing, in which multiple horizontal wells are drilled and fractured simultaneously (Figure 1). This approach enables one-time well placement, one-time fracture placement, and one-time transformation for unconventional oil and gas reservoirs. Unlike single-well fracturing, stress interference in PWF occurs not only between fractures but also between wells. The mutual interaction between wells and fractures generates a complex induced stress field, which, when superimposed on the formation stress, alters the stress distribution within the reservoir. This modification facilitates fracture diversion and promotes the formation of a more intricate fracture network [5]. In comparison to single-well fracturing, PWF offers several advantages, including reduced operational time and fewer equipment relocations, leading to a significant reduction in construction costs. Typically, PWF can increase average production by 21% to 55%, while costs can be reduced by more than 50% [6]. However, as the scale of operations expands exponentially, the evolution of the reservoir stress field becomes increasingly complex, and the mechanisms of production interference remain poorly understood, resulting in higher risks associated with PWF. To ensure the efficient implementation of PWF, it is essential to clarify the evolution of the stress field and the mechanisms governing the expansion of complex fracture networks [7]. In recent years, China's oilfields have systematically implemented an integrated development strategy characterized by multilayer systems, three-dimensional well patterns, large-scale well clusters, and factory-mode operations, which has driven innovations in multi-well platform deployment and three-dimensional reservoir stimulation techniques [8,9]. Notable examples include the Changqing and Xinjiang Ma 131 fields. Compared to 2019, fracturing times have increased by more than 30%, ensuring the effective implementation of shale oil and gas horizontal well transformation. In Jimusar, the "flat advancement" and "zipper fracturing" collaborative operation modes have been adopted, deploying five and three horizontal wells, respectively. On-site construction data indicate positive stress interference and three-dimensional reservoir transformation. Simultaneous fracturing is a key operational strategy within PWF that involves the concurrent stimulation of multiple wells. This technique enhances fracture complexity and reservoir connectivity by leveraging inter-well stress interference. Compared to sequential or single-well fracturing, simultaneous fracturing can accelerate the construction schedule, reduce operational costs, and significantly improve stimulated reservoir volume (SRV). Field applications in Jimusar, employing flat advancement and zipper fracturing modes, have demonstrated their effectiveness in achieving three-dimensional reservoir transformation. In the Tuha Oilfield, PWF has been used to improve recovery by breaking reservoir barriers between wells and increasing permeability. This was achieved through multi-well simultaneous fracturing and stress interference, which created interconnected fracture networks. These networks expanded the

stimulated reservoir volume (SRV), improved fluid flow, and enhanced overall permeability and production [10–13]. The development trajectory has progressed from simultaneous horizontal well network deployment to traditional zipper fracturing to improved zipper fracturing and ultimately to multi-well combination fracturing (Figures 2 and 3). While domestic PWF technologies have achieved notable results, further in-depth research is needed in areas such as detailed reservoir characterization, sweet spot identification, platform well layout optimization, well spacing optimization, and the design of three-dimensional transformation plans [14–18].



Figure 1. Equipment layout diagram for platform well fracturing (PWF) operations.

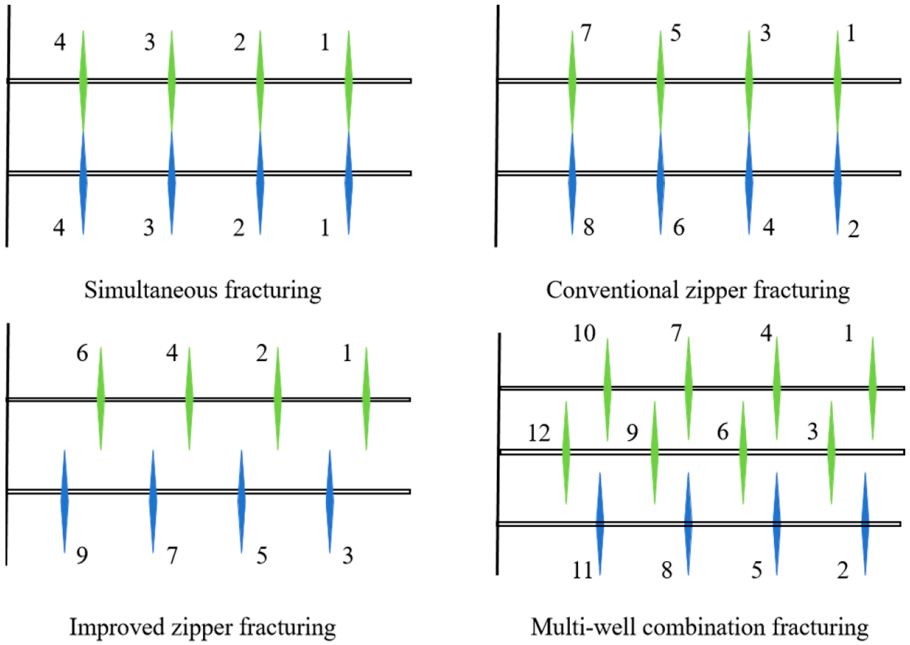


Figure 2. Schematic diagram of fracturing method transitions.

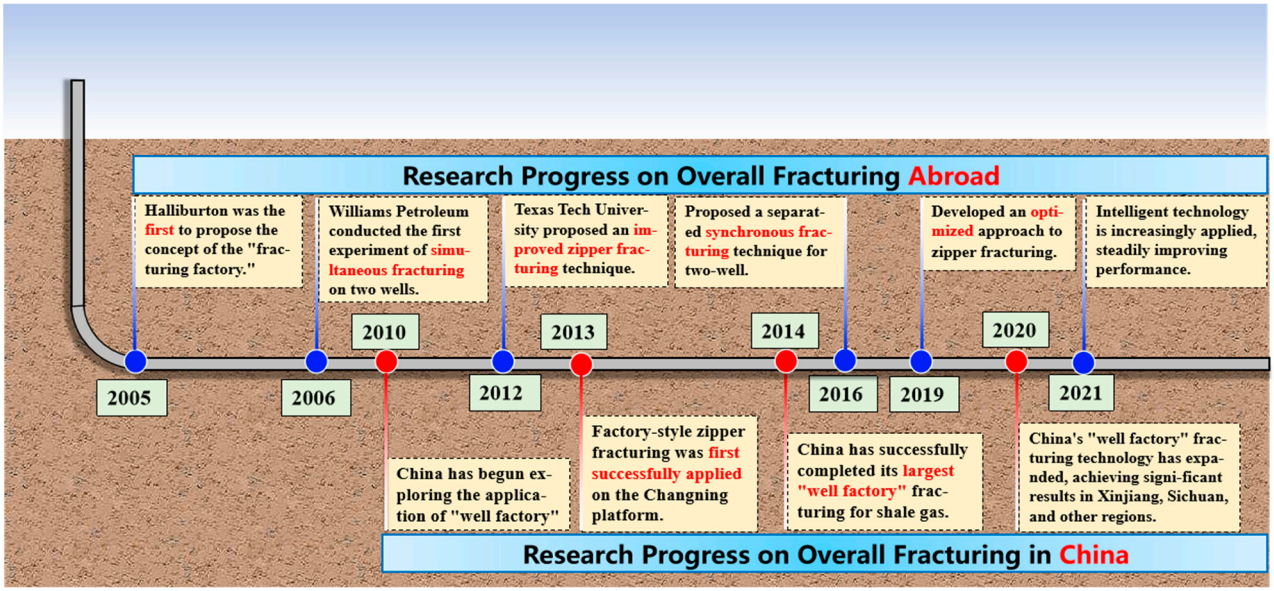


Figure 3. Development history of platform well ("well factory") fracturing at home and abroad.

This paper provides a comprehensive review of recent advancements in PWF technology for unconventional reservoirs, systematically summarizes progress in reservoir optimization techniques, evaluates the current challenges facing the technology, and outlines potential directions for future development. This study systematically reviews recent advancements in PWF optimization methods for unconventional reservoirs, with three primary objectives: (1) to establish a parameter optimization framework integrating geological constraints and economic indicators; (2) to evaluate the applicability of intelligent algorithms in high-dimensional fracturing parameter spaces; (3) to propose a development roadmap addressing China-specific challenges, such as data scarcity and complex lithology. The findings aim to bridge the gap between theoretical models and field applications, providing actionable insights for domestic shale oil/gas development.

2. New Progress in Optimization Research of PWF for Unconventional Reservoirs

2.1. Determination of Optimization Parameters and Objective Functions

2.1.1. Design of Optimization Parameters

Fracturing operations in unconventional reservoir platform wells are characterized by large-scale and complex processes, with fracturing effectiveness influenced by multiple factors. These factors primarily include geomechanical parameters (such as permeability, conductivity, and horizontal stress difference), fracturing design parameters (such as well placement, well spacing, and fracture spacing), and operational parameters (such as injection rate, fracturing fluid volume, and proppant volume) [19,20]. These factors interact with each other, collectively determining the final production outcomes and economic benefits. Therefore, optimizing fracturing parameters for unconventional reservoir platform wells is a complex optimization problem that requires a comprehensive consideration of multiple dimensions. It is crucial to select parameters based on actual production and operational conditions.

Currently, sensitivity analysis is a common optimization method, which includes single-factor and multi-factor analyses. Single-factor sensitivity analysis involves listing parameters that may affect fracturing effectiveness, adjusting each parameter individually while keeping others constant and observing their impact on the target variable. This helps identify the main influencing factors. However, single-factor analysis does not account for

interactions between parameters, making it difficult to achieve globally optimal parameters. In contrast, multi-factor sensitivity analysis, using an orthogonal experimental design, can more comprehensively consider the interactions between multiple parameters. This method provides a more thorough design scheme, although it still has limitations in terms of uniform parameter selection.

2.1.2. Design of Objective Functions

(1) Production Capacity as the Objective Function

Unconventional reservoirs are highly heterogeneous, making it challenging to accurately assess fracturing effectiveness. Well production capacity is often used as a key indicator to evaluate fracturing performance. Commonly used production capacity objective functions include annual cumulative oil production and estimated ultimate recovery (EUR). In recent years, researchers have conducted extensive studies and optimization work in the field of hydraulic fracturing, focusing on the significant impact of key parameters, such as fracture location, number of fracturing stages, and stage spacing on oil and gas production. In the development of reservoirs in the Changqing Oilfield, researchers constructed a horizontal well volumetric fracturing model using unstructured grids and optimized the fracturing design based on nonlinear seepage numerical simulation methods. Advanced algorithms such as radial basis function surrogate models, particle swarm optimization, and simulated annealing were employed to comprehensively optimize the production capacity of horizontal wells. The results showed that reasonable parameter selection could significantly enhance production capacity [21,22]. Additionally, by integrating geological and reservoir data, complex reservoir numerical models, including three-dimensional geological models, were established. These models, combined with seismic logging data, microseismic data, and geological, logging, fracturing, and production dynamic data, allowed for more accurate prediction of reservoir production dynamics. Studies have shown that well interference and stress evolution processes are crucial in optimizing well spacing and fracturing design parameters. These optimization designs have been thoroughly validated theoretically and have demonstrated practical value in actual production [23,24]. The theoretical validation of these designs was conducted using nonlinear numerical simulation methods based on unstructured grids, as well as coupled geomechanical–reservoir models. These simulations incorporated geological, logging, fracturing, and production data to model fracture propagation and production performance. The simulation results were then compared with actual production data from field applications, confirming the accuracy and effectiveness of the optimized parameters [25–27]. Furthermore, machine learning algorithms such as random forests and neural networks have been introduced to build more flexible production capacity prediction models for horizontal wells, aiming for long-term production maximization. These models can analyze the stress and strain in the fracturing zone in detail, considering the coupling of geomechanical parameters, thereby optimizing fracturing parameters to ensure stable long-term production capacity [28].

The above studies, using production capacity as the objective function for optimization, provide effective solutions for the complexity of on-site fracturing effectiveness evaluation and offer important theoretical support and practical guidance for oil and gas production capacity assessment and optimization design. However, although production capacity as an evaluation metric can reflect fracturing effectiveness, its limitation lies in its inability to achieve sustainable development and maximize economic benefits in oil and gas extraction.

(2) Net Present Value (NPV) as the Objective Function

Hydraulic fracturing operations in oil and gas fields involve significant investment and high risks. Therefore, conducting economic evaluations for individual wells and overall reservoir fracturing projects has become a crucial means of assessing their development

potential. Net present value (NPV), widely adopted as an economic evaluation model in the oilfield industry, is a key indicator for assessing the economic feasibility and future profitability of fracturing operations. By discounting future cash inflows and outflows, NPV clearly reflects the economic benefits of a project after considering the time value of money. Researchers can establish comprehensive and systematic formulas for calculating fracturing parameters in horizontal well networks by integrating geological and economic factors, providing robust data support and theoretical foundations for practical production decisions.

Researchers worldwide have extensively adopted NPV as a key objective for reservoir optimization, conducting comprehensive studies on relevant parameters through a series of optimization methods aimed at maximizing economic benefits. These studies not only focus on the economic indicators of individual wells but also conduct in-depth analyses of the overall economic benefits of well networks to ensure maximum return on investment. By developing multi-stage hydraulic fracturing models, response surface methods, geochemical analyses, integrated logging, and dipole–sonic logging, researchers have significantly enhanced the drainage area and economic production of reservoirs through refined reservoir modeling and parameter optimization [29,30]. Xu et al. [31] proposed a hierarchical optimization strategy that first optimizes individual wells and then the entire well network, using NPV as the objective function. By combining the Covariance Matrix Adaptation Evolution Strategy (CMA-ES) algorithm, they optimized well network parameters, demonstrating that the hierarchical strategy improves optimization efficiency while ensuring accuracy. Wang et al. [32], considering well and fracture interference, constructed a horizontal well seepage model based on economic benefit maximization, and optimized key operational parameters such as well spacing, fracture spacing, and conductivity. Sheng et al. [33] established an automatic optimization model for a fracture network–well network in fractured horizontal wells based on reservoir numerical simulation and the Simultaneous Perturbation Stochastic Approximation (SPSA) algorithm, using NPV as the objective function to synchronously optimize fracturing parameters, resulting in designs that match the geological conditions. Li et al. [34] developed a reservoir numerical model based on field data and established a production capacity prediction model for horizontal wells using machine learning algorithms. By coupling the machine learning model with the Particle Swarm Optimization (PSO) algorithm and using NPV as the objective function, rapid optimization of the fracturing parameters was achieved.

Currently, a small number of researchers have begun to integrate production capacity and economic benefits into a comprehensive multi-objective function framework to optimize hydraulic fracturing parameters. This approach not only enhances fracturing effectiveness but also ensures the maximization of economic benefits, providing new insights and directions for the sustainable development of oil and gas resources [35–38].

2.2. Integration of Fracture Propagation and Production Dynamics

Geological parameters and fracturing design parameters play a critical role in well production, as they collectively determine fracture propagation patterns, which directly influence production outcomes. To achieve efficient production, it is necessary to establish a mapping relationship between fracturing design parameters and final production outcomes through fracture propagation patterns. By predicting fracture propagation based on known fracturing design parameters, the production outcomes of wells can be inferred, a process known as integrated fracture propagation–production prediction simulation.

Significant progress has been made in this field. Lei et al. [39] developed a geomechanical integration program and proposed a reservoir stimulation method based on this program, demonstrating its ability to integrate hydraulic fracturing and oilfield develop-

ment. Zhu et al. [40] coupled an Embedded Discrete Fracture Model (EDFM) with local grid refinement to establish a fracturing production prediction model, achieving the seamless integration of fracture simulation and production prediction while addressing issues such as corner grid handling and inaccurate reservoir parameters. Tang et al. [41] combined dislocation theory and finite element fluid–solid coupling theory to establish a geomechanical model, studying the formation and propagation mechanisms of hydraulic fractures. They used the discrete lattice method to import fracture networks into reservoir models, establishing a production model for fractured horizontal wells in fan-shaped platform well networks, achieving the integrated simulation of fracture propagation and production dynamics. Wang et al. [42] simulated fracture propagation using the Displacement Discontinuity Method (DDM) and constructed a production prediction model by combining the LS-LR-DK grid system with CMG-GEM.

However, these studies still have limitations: (1) Differences in grid structures and fracture propagation models among simulators may lead to inconsistent results, reducing accuracy; (2) in complex geological conditions, grid distortions may occur, affecting the accurate simulation of fracture morphology; (3) in practical applications, insufficient integration of geological, engineering, and production data limits the reliability and applicability of the models.

2.3. PWF Optimization Method

2.3.1. Single-Factor Analysis

The single-factor analysis method treats a single fracture parameter as the optimization variable. By altering the value of this parameter, different reservoir simulation schemes are formulated to observe its impact on fracturing effectiveness. In practical applications, the single-factor analysis method is often used for preliminary analysis and to identify key factors influencing fracturing effectiveness. Through the in-depth study of individual factors, the degree of influence of each factor on fracturing effectiveness can be preliminarily assessed, providing a reference for subsequent research [43].

However, the single-factor analysis method has limitations. Since it only considers the influence of a single factor, it may overlook the significant contributions of other variables to fracturing effectiveness. Additionally, in actual reservoir production, the complex and variable nature of the reservoir environment often means that multiple parameters interact and constrain each other. Therefore, while the single-factor analysis method is valuable in the early stages of research, more comprehensive and in-depth analyses require multi-factor analysis methods. Only through multi-factor analysis can fracturing effectiveness be evaluated more comprehensively and accurately, leading to the development of more effective fracturing designs [44].

2.3.2. Orthogonal Testing Method

The orthogonal experimental method is a multi-factor experimental design approach that offers stronger comprehensive analysis capabilities compared to traditional single-factor analysis methods. Through the orthogonal experimental method, the influence of multiple parameters on the objective function (such as production or net present value) can be studied in a single experiment, providing a more comprehensive understanding of the interactions between factors. The core idea is to quantify the interactions between parameters through cross-group experimental design. This method uses orthogonal tables to design experiments, ensuring comprehensiveness and efficiency. The rows and columns of the orthogonal table represent factors and levels in the experiment, respectively. By selecting appropriate experimental combinations, the number of experiments can be minimized while ensuring data integrity. In well fracturing and production optimization, the

orthogonal experimental method is widely used to quantify the impact of parameters, such as fracture conductivity, well spacing, and fracture length, on production outcomes and optimize parameter combinations to enhance production capacity. This method, combined with numerical simulation techniques, effectively evaluates the impact of different parameter combinations on well productivity and proposes optimization solutions for stable and increased production [45,46].

Despite its significant applications in fracturing design optimization, the orthogonal experimental method has limitations when dealing with uncertainties in reservoir geology. This optimization method requires repeated operations on reservoir simulation software(e.g., Petrel2022, CMG2024 and Gohfer9.3), making the process cumbersome and time-consuming, which limits the ability to quickly obtain optimal overall fracturing designs. Additionally, due to the complexity of reservoir geology, the orthogonal experimental method may not fully consider all influencing factors, leading to deviations in optimization results. Therefore, to address uncertainties in reservoir geology, more efficient and comprehensive optimization methods need to be explored to obtain optimal overall deployment solutions in a shorter time, improving the effectiveness and efficiency of reservoir development.

2.3.3. Intelligent Optimization Method

Intelligent optimization algorithms and machine learning algorithms are increasingly being applied in oil and gas engineering, becoming important tools for promoting resource development and enhancing production capacity. Intelligent optimization algorithms, such as genetic algorithms, particle swarm optimization, and simulated annealing, can find optimal solutions in complex, multi-dimensional spaces, addressing problems that traditional optimization methods struggle to handle. Machine learning algorithms, through data-driven approaches, learn from historical data to predict or classify, demonstrating unique advantages in handling nonlinear, non-stationary, and high-dimensional data. In solving practical problems in oil and gas field production, the potential of intelligent optimization algorithms and machine learning algorithms is increasingly evident. Yao et al. [47] optimized fracturing parameters for shale gas reservoirs using a modified variable-length particle swarm optimization (MVPSO) algorithm, resulting in complex fracture propagation patterns and a linear relationship between conductivity and fracture half-length. Zhang et al. [48] used an improved neural network algorithm (M-NNA), combined with the displacement discontinuity method and the embedded discrete fracture model, to study fracture propagation and production outcomes in shale gas reservoirs under the influence of natural fractures. They optimized reservoir parameters with NPV as the objective function to achieve higher economic benefits. Wang et al. [49] addressed the computational burden and decision-making challenges of existing optimization methods by proposing a hybrid surrogate model and transfer learning technique (SATS-WSF) for optimizing horizontal well spacing and stage spacing. The results showed that this method effectively utilized the synergy between multiple single surrogate models, improving the accuracy and reliability of optimization solutions. By effectively combining intelligent optimization algorithms with machine learning algorithms, Lu et al. [50] used deep neural networks and particle swarm optimization, along with machine learning algorithms, to optimize production predictions and fracturing parameters for shale oil. By establishing a DNN model database, they evaluated production capacity. The study showed that the DNN model performed best in production prediction, and using PSO to optimize parameters significantly increased oil production and NPV. Zhang et al. [51] proposed an integrated intelligent optimization system tailored for holistic fracturing designs in platform well groups, achieving improved efficiency and effectiveness in field applications. Li et al. [34]

proposed a hybrid ML-PSO model combining machine learning (ML) and particle swarm optimization (PSO) to overcome the limitations of current production prediction methods. By establishing a machine learning model and conducting sensitivity analysis, they identified parameters with the greatest impact on production and NPV. By optimizing fracturing operation parameters, they successfully increased NPV, demonstrating the advantages of machine learning in optimizing horizontal well designs. In summary, a wide range of optimization techniques—including classical methods, numerical simulations, evolutionary algorithms, and response surface methodology (RSM)—have been effectively applied in PWF design and performance analysis. These methods provide complementary strengths in terms of accuracy, flexibility, and computational efficiency. By integrating data-driven approaches with physical modeling and real-time monitoring, future optimization frameworks can achieve more reliable, efficient, and adaptive fracturing designs tailored to reservoir complexity [52]. Apart from system-level challenges, several limitations exist within the current simulation-based optimization studies, as illustrated in (Figure 4) Fracture and grid coupling methods involve four core aspects—fracture propagation simulation, productivity simulation, parameter optimization, and iterative processes—all of which are susceptible to uncertainties and model mismatches. These limitations include the following: (1) Differences in grid structures and fracture propagation models among simulators may lead to inconsistent results, reducing accuracy; (2) in complex geological conditions, grid distortions may occur, affecting the accurate simulation of fracture morphology; (3) in practical applications, insufficient integration of geological, engineering, and production data limits the reliability and applicability of the models.

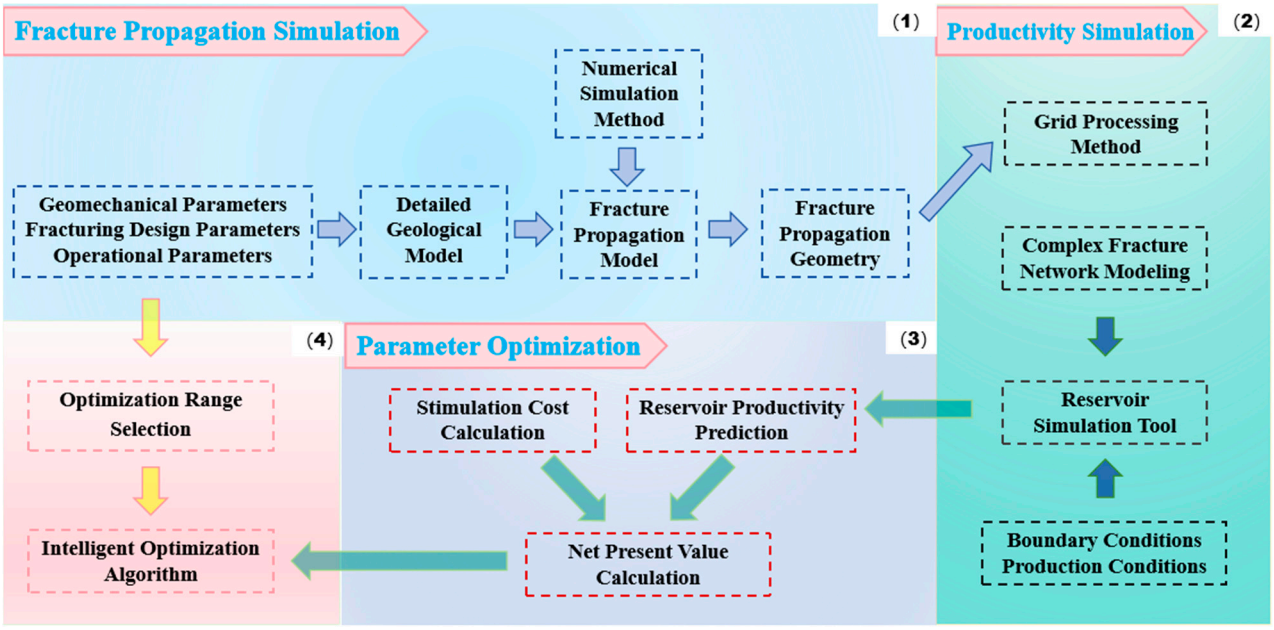


Figure 4. Fracture and grid coupling methods: (**1**) simulation of fracture propagation; (**2**) simulation of productivity; (**3**) parameter optimization; (**4**) iterative process.

3. Challenges of PWF Technology in Unconventional Reservoirs

Currently, China's exploration of PWF in unconventional reservoirs is still in its infancy. Although the fracturing parameters have reached the technical standards of North America, preliminarily verifying the feasibility of the technology, the fracturing effectiveness and construction costs have not yet met the expected standards. This indicates that, given the complexity of PWF in unconventional reservoirs, many issues still need to be urgently addressed, as outlined below:

(1) Complex Geological Conditions of Unconventional Reservoirs

Unconventional reservoirs typically exhibit high heterogeneity and low permeability, characterized by nanodarcy-level features. The fluid flow patterns in such reservoirs are highly variable, and fracture propagation patterns are complex and diverse. Notably, natural fractures are commonly present in these reservoirs, forming intricate fracture networks and significantly increasing the difficulty of predicting fracture morphology. The presence of natural fractures can lead to changes in in situ stress distribution, causing localized stress concentration or dispersion, further influencing fracture propagation paths and, in extreme cases, damaging the formation itself. The high heterogeneity and complex fracture networks in unconventional reservoirs directly increase the risk of uneven fracture propagation and ineffective reservoir coverage during PWF operations. This leads to higher fracturing fluid consumption and lower stimulated reservoir volume (SRV) efficiency, ultimately reducing the economic viability of large-scale PWF deployments [53]. Therefore, for unconventional reservoirs in different blocks, it is essential to conduct localized fine-scale modeling and in-depth analysis to fully characterize their unique geological features and flow behaviors.

(2) Inability to Quantitatively Characterize Complex Fracture Networks

Quantitatively characterizing complex fracture networks is a significant challenge in fracturing optimization. Currently, the characterization of complex fracture networks is often limited to simple planar fractures. Fracture modeling methods are mainly divided into direct and indirect approaches. Direct methods rely on discrete or embedded fracture network models to digitally represent the fracture propagation process in the formation. However, due to the nonlinear, multi-scale, and complex physical processes involved, the computational complexity is high, and the accuracy of simulation results is often difficult to evaluate [54,55]. Indirect methods typically use fractal principles or statistical analysis to assess fracture network characteristics based on overall structures, validated through laboratory experiments, microseismic monitoring, or production history matching. However, laboratory experiments are limited in scale and cannot replicate the actual reservoir environment, making their results only suitable for reference and theoretical support.

(3) Lack of Accurate Geological and Production Data Support

In unconventional oil and gas reservoirs, accurate geological and production data are crucial for on-site operations and simulation optimization. However, in actual production sites, data acquisition is challenging and costly, and the accuracy of the data still needs verification. The lack of sufficiently precise geological and production data to support optimization design and overall on-site operations leads to significant uncertainties in fracturing design and effectiveness evaluation, posing challenges for PWF optimization [56,57]. The scarcity of reliable geological and production data compels operators to rely on analog field data and empirical approaches, introducing substantial uncertainty in development planning. This data gap hinders precise sweet spot identification and optimal well placement, leading to inefficient resource utilization and diminished economic returns from PWF operations.

4. Development Direction of Fracturing Technology for Platform Wells in Unconventional Reservoirs

4.1. Strengthen the Integrated Research of Geology and Engineering and Scientifically Design the Fracturing Plan

The production capacity of oil and gas wells is a comprehensive reflection of geological, reservoir, and engineering factors. Emphasizing integrated geological engineering research means leveraging engineering thinking to maximize the geological potential of reservoirs.

This process requires in-depth research at both the geological exploration and on-site construction levels to optimize the development of oil and gas resources.

First, at the geological level, it is essential to study key characteristics such as hydrocarbon-bearing intervals, fluid permeability, and rock mechanical behavior. By comprehensively evaluating reservoir "sweet spots"—areas with the highest production potential, "sweetness" (relative production capacity), and fracability—solid data support can be provided for on-site operations [58].

Second, at the engineering level, optimizing fracturing design and actual construction processes is critical. These engineering implementation stages have a direct and significant impact on fracturing effectiveness and ultimate production outcomes. Strengthening integrated geological engineering analysis and design allows for the full acquisition and analysis of reservoir information, optimizing well placement, fracturing design, and injection-production strategies. This approach ensures the construction of well networks that are highly compatible with reservoir properties, improving reservoir utilization and achieving an economically optimal match between geological parameters, reservoir parameters, and engineering factors.

Furthermore, the concept of integrated geological engineering should extend throughout the entire process, not limited to the drilling and fracturing stages but also encompassing the entire oil and gas production lifecycle. This dynamic management strategy for the full lifecycle helps achieve the optimal configuration of production processes, ensuring the sustainable development of oil and gas resources and maintaining dynamic balance across all stages, thereby enhancing overall production efficiency and economic benefits.

4.2. Enhanced Fracturing Detection and Intelligent Auxiliary Equipment

4.2.1. Fiber Optic Monitoring Technology for Fracturing of Unconventional Oil and Gas Wells

Fiber optic monitoring technology for oil and gas wells is a novel monitoring technique and one of the most accurate methods currently available for monitoring downhole geological parameters and production indicators. Traditional fiber optic technologies mainly include Distributed Acoustic Sensing (DAS) and Distributed Temperature Sensing (DTS) [59–61]. This technology uses fiber optic sensors to monitor and analyze the operational status of oil and gas pipelines, capturing key parameters such as temperature, pressure, and flow rate in real time. It primarily includes disposable and permanent fiber optic technologies. Disposable fiber optics have relatively low deployment costs and can reduce the risk of equipment damage and wellbore impairment. Several platforms have already integrated disposable fiber optics with DAS and DTS technologies to monitor field data and fracture parameters [62]. Compared to disposable fiber optics, permanent fiber optics have higher costs but excel in data transmission stability, real-time performance, and capacity, making them more suitable for large-scale data transmission applications. Future fiber optic monitoring technologies should combine the advantages of both disposable and permanent fiber optics, reduce equipment costs, enhance maintainability, and improve the real-time accuracy of data transmission. Additionally, integrating automation technologies can improve construction efficiency and ensure safety.

4.2.2. Real-Time Friction Data Measurement Based on Downhole Sonic Technology

Downhole acoustic technology uses the principles of acoustic wave propagation to obtain downhole information and is an effective means of real-time monitoring and data acquisition. This technology can acquire downhole friction data, which is crucial for evaluating construction effectiveness and adjusting construction parameters [63]. However, surface acoustic technology is susceptible to underground environmental interference, significantly affecting data accuracy. Therefore, improving the accuracy of acoustic data

measurement can be achieved through the following strategies: (1) selecting high-precision or high-sensitivity surface acoustic monitoring equipment or choosing appropriate acoustic detection frequencies, as different frequencies are suitable for different formation depths and geological conditions; (2) enhancing data analysis algorithms and techniques to precisely process and analyze acquired acoustic data, extracting and interpreting valid information [64,65].

4.2.3. Fracturing Fluid Real-Time Tracking and Monitoring Equipment

Real-time fracturing fluid monitoring equipment is widely used in the petroleum industry. With continuous technological advancements and increasing field demands, this equipment is constantly evolving to meet more complex engineering requirements and monitoring precision. By monitoring the flow path and rate of fracturing fluids, this equipment can prevent fluid blockages and losses in the reservoir. Additionally, analyzing the fluid's path and rate can determine the depth and direction of fracturing fluid penetration, thereby assessing whether the desired fracturing effect has been achieved [66]. Current real-time fracturing fluid monitoring devices have made significant technological progress, enabling real-time monitoring and control of multiple parameters. These devices use various sensors and computer systems to monitor physical and chemical parameters, such as viscosity, pH, temperature, fluid level, and density. Despite their advantages, including real-time monitoring, multi-parameter monitoring, high automation, and remote data transmission, these devices still face challenges such as data inaccuracies, incomplete monitoring, low efficiency, and limited applicability. Future research should focus on improving data accuracy, expanding monitoring parameters, simplifying device operation, and enhancing system applicability.

4.2.4. Unconventional Hydraulic Fracture Diagnosis Technology

Unconventional hydraulic fracture diagnostics technology uses advanced imaging techniques and computational methods to achieve high-precision diagnosis and monitoring of hydraulic fractures. Imaging technology is the core of this field, utilizing seismic waves, acoustic waves, X-rays, and other imaging methods to obtain detailed images of the reservoir, revealing the pore structure characteristics of the rock [67]. Improvements in computational methods are also a critical component of unconventional reservoir hydraulic fracture diagnostics. Advances in computer technology have made it possible to process and simulate complex geological data. By establishing detailed geological models and integrating actual measurement data, the generation and propagation of fractures during hydraulic fracturing can be simulated [68]. Current unconventional hydraulic fracture diagnostics technologies have made significant progress, including tracer analysis, fiber optic technologies (such as DTS and DAS), tiltmeters, microseismic monitoring, and diagnostic fracture injection tests [69].These technologies are used to estimate fracture length, height, width, complexity, orientation, cluster efficiency, fracture uniformity, and proppant distribution. Distributed Temperature Sensing (DTS) and Distributed Acoustic Sensing (DAS) technologies have emerged as powerful tools in unconventional hydraulic fracture diagnostics. DTS enables continuous temperature profiling along the wellbore, which can be used to identify fluid entry points and infer fracture activity. DAS, on the other hand, captures acoustic signals that help characterize fracture propagation and proppant movement in real time. Together, these technologies significantly improve the spatial and temporal resolution of downhole diagnostics, facilitating a better understanding of complex fracture networks and aiding in more precise fracturing design.

In practical applications, the advantages of unconventional hydraulic fracture diagnostics technology are evident. First, high-precision imaging and computation allow for more

accurate determination of reservoir locations and properties, avoiding blind extraction and resource waste. Second, precise fracture diagnostics enable the optimization of fracturing designs, reducing fracturing fluid usage and minimizing environmental pollution. Additionally, real-time monitoring helps detect and address anomalies during fracturing, ensuring construction safety [70].

However, current hydraulic fracture diagnostics technologies still have limitations [71,72]: the description of fracture geometry, complexity, and proppant distribution remains in its early stages, and the quantitative characterization and visualization of complex hydraulic fractures in reservoirs need improvement. Therefore, future hydraulic fracture diagnostics technologies should focus on (1) applying advanced mathematical modeling techniques, such as data inversion and geomechanical modeling, to reduce diagnostic uncertainty; (2) leveraging machine learning to enhance diagnostic accuracy and efficiency; (3) developing new diagnostic technologies to overcome current challenges and address the evolving demands of unconventional reservoir development.

In addition, despite the technical advantages, several factors continue to limit the widespread field application of advanced diagnostic technologies. These include high installation and maintenance costs—especially for permanent fiber-optic systems, operational complexity in high-temperature and high-pressure environments, data transmission limitations in deep wells, and challenges in interpreting large volumes of data influenced by environmental noise. These barriers reduce the feasibility of large-scale deployment in many oilfields.

4.3. Develop Intelligent Optimization and Real-Time Control Technology for PWF

Platform well fracturing (PWF) optimization is one of the key technologies in the development of unconventional reservoirs. Advancing this technology can significantly enhance the effectiveness and efficiency of hydraulic fracturing operations. However, most current PWF optimization approaches remain confined to pre-fracturing design and post-construction evaluation stages, making real-time monitoring and analysis of fracturing parameters difficult to achieve. To date, only a few international studies have realized integrated systems that combine PWF optimization with real-time control, while such integrated platforms are still lacking in domestic applications.

To establish such platforms, it is first necessary to develop a real-time monitoring module capable of acquiring key downhole data online. Second, advanced algorithmic technologies and intelligent optimization software (e.g., Matlab2022b, Python3.9) must be employed to analyze and adjust fracturing parameters based on real-time data. Lastly, the platform should undergo regular evaluation and continuous improvement to refine its algorithms and models, thereby enhancing the accuracy and reliability of optimization outcomes (Figure 5).

In addition to large-scale hydraulic fracturing, other enhanced oil recovery (EOR) techniques—such as gas injection (e.g., CO_2, N_2), steam flooding, and chemical flooding—have been successfully applied in various unconventional reservoirs to improve oil and gas production. These methods can be employed either independently or in combination with hydraulic fracturing, depending on the specific reservoir characteristics and development objectives, thereby achieving higher recovery efficiency.

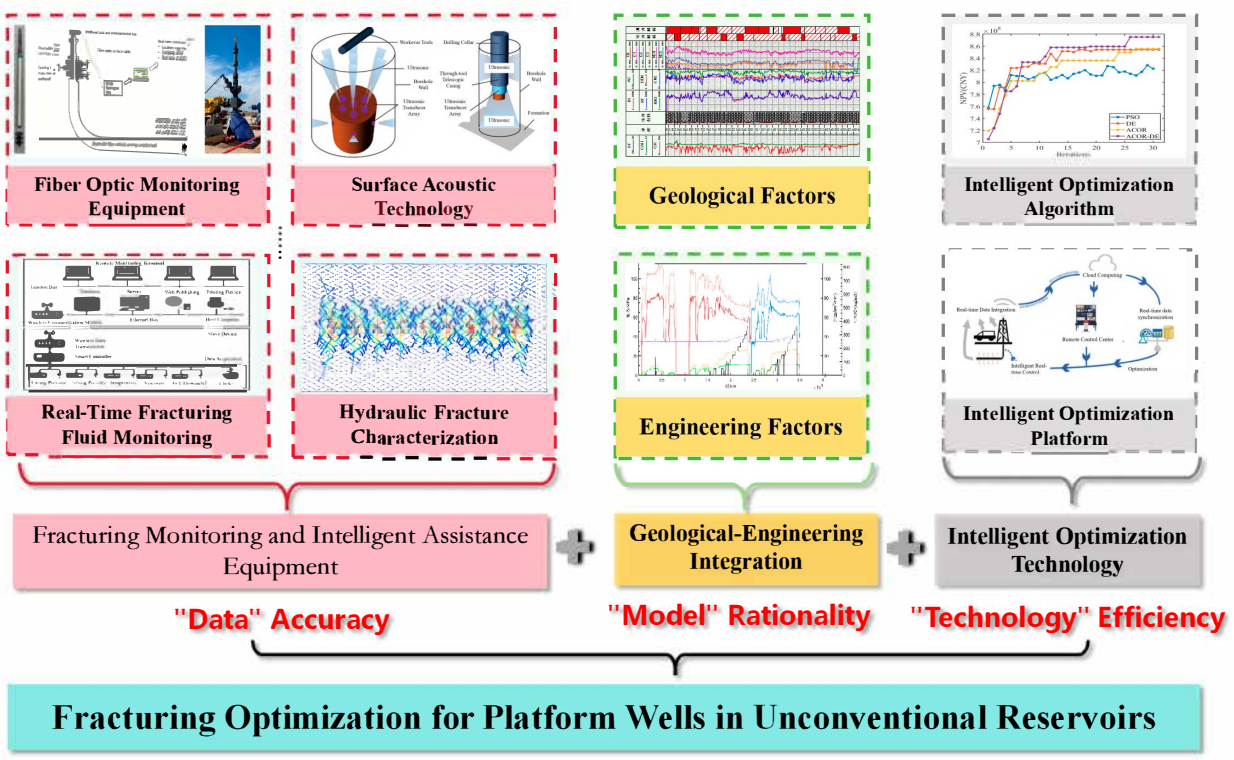


Figure 5. Development of intelligent optimization and real-time control technology for PWF.

5. Conclusions

This study analyzed the current research and challenges in PWF technology and presents the following conclusions with future development directions:

(1) Future work must strengthen the coupling between reservoir characterization and fracturing design. This includes developing China-specific geological models that account for local formation properties while incorporating real-time monitoring data to validate and refine simulations. The successful pilot projects in Changqing and Xinjiang demonstrate the potential of such integrated approaches.

(2) While intelligent algorithms show advantages in parameter optimization, their full potential requires integration with field operations. This involves not only algorithm development but also the creation of decision-support systems that can process field data, account for China's data limitations, and provide actionable recommendations for fracturing design adjustments.

(3) The path forward must balance technical and economic considerations, particularly in addressing China's specific challenges of high monitoring costs and complex reservoir conditions. Hybrid monitoring solutions and phased implementation strategies can help achieve this balance while accumulating the operational experience needed for continuous improvement.

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