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Comprehensive Treatment Technology for Downhole Complex Problems in Old Oilfields and Its Application Effect

Xiaoning Cheng
CCDC Changqing Down Hole Technology Company, Xi'an, China

Abstract: Old oilfields have entered a stage of high water cut and high recovery, characterized by complex downhole problems such as casing damage, crossflow, and blockage. Traditional single-treatment technologies have significant limitations. This paper proposes an intelligent integrated treatment technology system that integrates big data, artificial intelligence, and digital twins to address the complex downhole challenges faced by high water-cut old oilfields in my country, including reservoir blockage, casing damage, and inter-layer interference. The system achieves precise diagnosis through multi-source data integration, machine learning, and digital twins; it develops core technologies such as integrated wellbore repair and reservoir-based collaborative unblocking and permeability enhancement, and supports dynamic optimization processes based on big data. Field applications show that this system achieves a 267% increase in oil production, 12 months of recurrence-free casing repair, and a 15 percentage point reduction in water cut in typical wells, significantly improving single-well productivity and the effectiveness of treatments while reducing operating costs. This system represents a shift from "segmented treatment" to "systematic rehabilitation" in the management of downhole problems in old oilfields, providing key technical support for the precise and intelligent development of secondary development of old oilfields.

Keywords: Old Oilfield; Complex Downhole Problems; Integrated Treatment Technology; Well Workover Operations; Application Effects

1. Introduction

As global oil and gas exploration and development gradually extends to deeper, more complex structures and unconventional resources, old oilfields, as an important cornerstone for stable oil and gas production, are becoming increasingly prominent. Faced with the reality of rising costs and increasing difficulty in discovering new blocks, the stable production and redevelopment of old oilfields have become the "ballast" for ensuring national energy security. However, after long-term high-intensity exploitation and water injection development, the main oilfields in eastern my country have generally entered the "double high" stage of high water cut and high recovery rate. The development contradictions have shifted rapidly from macroscopic interlayer and intralayer contradictions to microscopic pores and complex wellbore spaces, giving rise to a series of complex downhole problems that are difficult to manage and restrict efficient development, such as casing damage, interlayer/external flow, near-well deep blockage, sand production and complex engineering accidents [1]. These "old diseases" not only lead to a decline in the utilization rate of oil and water wells and a surge in the frequency of maintenance operations, but also seriously damage the original injection and production well network, making it impossible to effectively utilize a large amount of remaining oil, and the sustainable development of old oilfields faces severe challenges [2]. Traditional solutions often employ "surgical" treatments targeting single symptoms, such as mechanical casing repair, chemical water shut-off, or unblocking. While effective for a certain period, their limitations are glaringly apparent in today's complex operating conditions: First, problem diagnosis is often one-sided, relying on experience and localized data, making it difficult to grasp the full picture and root causes of the wellbore-formation coupling system; second, the measures have poor adaptability, with single technologies struggling to address complex problems involving multiple issues, resulting in short-term effectiveness and even secondary damage; third, economic benefits are marginalized, with repetitive and high-cost operations eroding already meager profit margins [3-4]. Therefore, transforming the governance philosophy from "segmented treatment" to "systemic rehabilitation," and developing a comprehensive treatment technology system capable of accurate diagnosis, collaborative governance, and long-term maintenance, is the only way to achieve cost reduction, efficiency improvement, and in-depth potential tapping in old oilfields.

Currently, technological development is providing a strong driving force for this transformation, showing a clear trend of intelligence, integration, and digitalization. In the diagnostic stage, intelligent early warning and diagnostic technology for downhole problems based on big data and machine learning is emerging. It can integrate multi-source data such as geology, engineering, and production to achieve early identification and quantitative analysis of the causes of complex problems, providing "navigation" for precise policy implementation [5]. At the treatment process level, technological innovation focuses more on multi-technology collaboration and material innovation. For example, intensive processes such as injection and production in the same well reduce the number of tubing strings and potential failure points from the source through wellbore space reconstruction, representing the system thinking of wellbore engineering design [6]. Meanwhile, new slow-release acid, self-directing agent and other intelligent materials developed for low-pressure and contaminated blocks can achieve more efficient and deeper unblocking and transformation [7,8]. The oilfield full life cycle management concept with digital twin as the core is realizing a paradigm shift from passive fault handling to proactive system optimization by constructing virtual mapping entities, providing an unprecedented platform for scheme simulation, risk prediction and effect iteration of comprehensive treatment technology [8-10]. Despite the promising prospects, a significant gap remains in translating advanced concepts and technologies into universally applicable, efficient, and scalable field solutions. The challenge lies in how to organically integrate discrete technical modules into a unified technical process that is accurate in diagnosis, scientific in decision-making, reliable in construction, and closed-loop in evaluation, based on the specific geological and development characteristics of a particular oilfield.

This study focuses on typical high-water-cut old oilfields in my country, directly addressing core downhole challenges such as casing damage, crossflow, and complex blockage. The aim is to break down technological barriers and integrate engineering geology, intelligent diagnostics, new materials and processes, and digital management to develop and establish a comprehensive technical system for handling complex downhole problems in old oilfields. This system comprises "data-driven diagnostics, key technology breakthroughs, dynamic process optimization, and real-time effect evaluation." This paper systematically elucidates the system's construction logic, core technological innovations, and integrated application methods. Through detailed field application cases, it quantitatively demonstrates its significant value in restoring wellbore function, increasing single-well productivity, extending the effectiveness of measures, and improving the development efficiency of blocks. The goal is to provide solid technical support and a practical paradigm for promoting the precise, intelligent, and efficient secondary development of old oilfields.

2. Comprehensive Diagnostic Methods for Complex Downhole Problems in Old Oilfields

2.1 Integration and Feature Engineering of Multi-Source Heterogeneous Data

Old oilfields accumulate massive amounts of diverse "data assets" during their production cycles, including well logging curves, production dynamics (production volume, water cut, pressure), engineering operation records (well workover history, intervention parameters), downhole monitoring (temperature, pressure, flow rate), and geological model data. The bottleneck of traditional diagnostics lies in the fact that this data exists in "information silos." This system first establishes a unified data lake to clean, align, and standardize multi-source heterogeneous data. A key step is time-series feature engineering, such as calculating the rate of change, variance, and trend slope of key parameters (e.g., injection pressure, production index), and extracting correlation features reflecting wellbore integrity and reservoir connectivity, such as the response relationship between casing pressure and fluid volume, and the correlation between water channeling velocity and pressure gradient. These features provide high-dimensional, information-rich input for subsequent intelligent analysis.

2.2 Intelligent Problem Identification and Risk Classification Based on Machine Learning

Based on feature engineering, machine learning algorithms are introduced to construct intelligent diagnostic models for complex downhole problems. For datasets with clear historical labels (such as known casing deformation wells and severely blocked wells), supervised learning algorithms (such as random forests and gradient boosting decision trees) can be used for training to achieve fault classification and identification of new wells or wells in unknown states [11]. For a large amount of daily production data lacking clear labels, unsupervised learning algorithms (such as cluster analysis and isolated forests) are applied to discover abnormal patterns, identify "sub-healthy" wells that deviate from normal production patterns, and achieve early warning. The model outputs not only the problem type, but also the risk probability and severity level. For example, the system can predict the risk probability of a well experiencing severe sand production or casing failure within the next 3 months and classify it accordingly (low, medium, high) to provide a quantitative basis for decision-making.

2.3 Simulation and Causal Deduction of Wellbore-Formation System Based on Digital Twin

In order to gain a deeper understanding of the causes of the problem and test the treatment plan, this system constructs a wellbore-formation collaborative digital twin model for key wells or typical well groups. The model takes the integrated geomechanical model, fluid flow model and tubing mechanics model as the core, and continuously synchronizes and calibrates with real-time/historical production data through the data interface, making it a high-fidelity virtual mapping of the physical entity [12].

When the intelligent diagnostic module identifies anomalies (such as a sudden increase in injection pressure or abnormal sand content in the produced fluid), the digital twin model initiates a causal simulation. Engineers can operate the virtual model to simulate different causes: Is it blockage caused by near-wellbore fracture closure? Is it localized casing deformation leading to narrowing? Or is it reservoir particle migration? By comparing the matching degree between the simulation results and actual monitoring data, the root cause can be pinpointed most accurately. In addition, the model serves as a "virtual testbed" for treatment measures, simulating the impact of different casing repair schemes, plugging agent injection schemes, or unblocking processes on the system before implementation, optimizing construction parameters, and predicting potential risks, thereby transforming the traditional "construction-trial and error" model into a precise "simulation-optimization-construction" model.

3. Construction of a Comprehensive Technology System for Handling Complex Downhole Problems in Old Oilfields

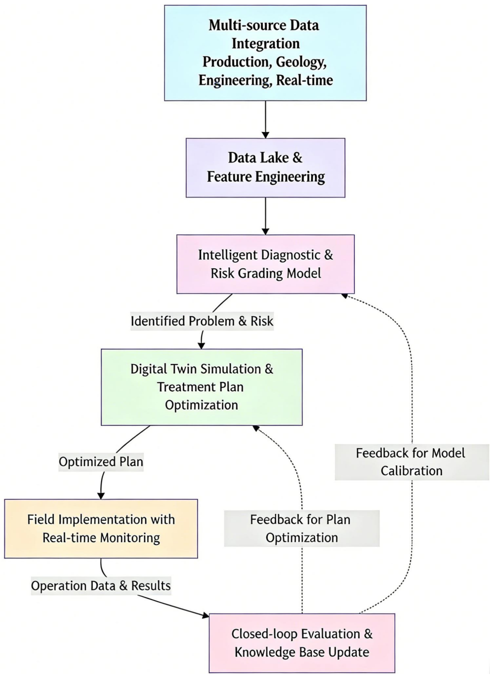

Figure 1. Workflow of the Comprehensive "Diagnosis-Treatment-Evaluation" System

Based on the precise diagnosis presented in Chapter 2, this chapter proposes and constructs a comprehensive technology system integrating "diagnosis-decision-collaborative processing-evaluation" (see Figure 1). This system emphasizes synergistic effects between technologies, rather than simple aggregation, aiming to solve complex problems through a systematic approach.

3.1 Integrated Repair Technology Centered on Wellbore Function Restoration

For wellbore failures (such as casing damage or tubing corrosion), this system advocates shifting from simple repairs to systematic functional restoration.

Composite material reinforcement repair technology, targeting corrosion-perforated or slightly deformed casing, employs high-performance fiber composite materials for internal wellbore reinforcement. This technology not only seals leaks but also significantly improves the overall compressive strength of the casing. Its ease of application avoids the significant costs and risks associated with traditional casing replacement.

Adaptive intelligent plugging technology, targeting inter-layer flow or external channeling, utilizes an adaptive gel plugging agent with adjustable performance under formation temperature and salinity. This plugging agent intelligently identifies and preferentially enters high-permeability flow channels, forming a high-strength seal while minimizing damage to low-permeability production layers, achieving water plugging without oil loss.

The same-well injection and production technology is a strategic solution for sections that are difficult to develop economically and effectively using conventional methods due to complex well conditions or special distribution of remaining oil [13]. This technology achieves water injection and oil production of the target layer through a single tubing string, which not only greatly simplifies the well structure and reduces tubing string failure points, but also avoids inter-layer interference problems in physical space. It is an innovative well treatment strategy for realizing "well regeneration" and efficient potential tapping in specific old oilfield blocks.

3.2 Reservoir and Wellbore Synergistic De-clogging and Permeability Enhancement Technology

Addressing reservoir damage and near-wellbore blockage issues, the technology emphasizes both "damage relief" and "reconstruction of effective flow channels." Deep synergistic acidizing de-clogging technology utilizes a composite acid system containing slow-release acid, chelating agents, and surfactants for complex blockages caused by inorganic scale and drilling fluid contamination. Combined with digital twin model-optimized injection rates and flow rates, it achieves deep acid penetration and uniform dissolution of contaminants, avoiding secondary precipitation.

Physicochemical combined permeability enhancement technology creatively combines nano-injection technology with low-pressure pulse wave de-clogging technology for low-pressure, highly water-sensitive reservoirs. Nanoparticles alter rock surface wettability and reduce fluid flow resistance, while low-pressure pulse waves utilize vibrational energy to remove microscopic blockages without damaging the formation framework. The synergy of these two technologies significantly improves the response rate and effectiveness of measures in low-pressure reservoirs.

3.3 Dynamic Optimization and Intelligent Decision-Making Process based on Big Data and Digital Twin

The core competitiveness of the integrated processing system lies in its "dynamic perception, real-time optimization and intelligent decision-making" capabilities, which are driven by big data analysis and digital twin technology throughout the process. In the digital twin model, diagnostic results and geological engineering data are imported to simulate the entire process of the proposed unblocking, repair or same-well injection and production scheme. By comparing the simulation effects of different schemes (such as increased oil production, pressure changes, and validity period), combined with the economic evaluation model, the optimal technology combination and construction parameters are intelligently recommended [13]. During construction, downhole sensors and ground data are transmitted to the control center in real time. The big data analysis platform continuously compares the real-time construction curves (pressure, displacement, concentration) with the "ideal safety window" generated by the digital twin model. Once a deviation occurs (such as abnormal pressure indicating the formation of new fractures or encountering large channels), the system will issue an immediate warning and can automatically or assist decision-makers in dynamically adjusting the pumping program to achieve risk-controllable "adaptive" construction. After the measures are completed, the effects are quickly evaluated using the real-time recovered production data and well test interpretation results. All data, model parameters and implementation results are fed back to the big data platform and digital twin model for calibration of model accuracy, optimization of algorithms, and formation of a structured case knowledge base [12]. This closed-loop process enables the entire technology system to have the ability to continuously learn and improve itself, laying the foundation for continuous optimization of the processing solution and successful replication in new well locations.

4. Case Study of Integrated Technology for Handling Complex Downhole Problems in Old Oilfields

To verify the effectiveness and practicality of the integrated treatment technology system proposed in Chapters 2 and 3, this chapter selects three representative field application cases from a typical high water-cut old oilfield in eastern my country for analysis. The cases cover major complex downhole problems such as reservoir composite damage and blockage, casing failure under pressure, and dispersed extraction of residual oil in multi-layer systems. The application process and effects are detailed in Table 1 to demonstrate the systemic advantages and flexible adaptability of integrated technology.

Table 1. Summary of Key Parameters and Effects for Field Application Cases

Case	Target Well Type & Core Problem	Key Technologies Applied	Main Technical Indicators Before/ After Treatment	Economic & Technical Effect Summary
Case 1	Production Well; **Low Pressure, High Water Cut, Compound Formation Damage** (scale, fines migration, emulsion)	Digital Twin Simulation, Intelligent Acidizing System, Nano-fluid Post-flush	**Fluid Rate:** 8.5 → 20.3 m³/d **Oil Rate:** 0.6 → 2.2 m³/d **ater Cut:** 92.5% → 89.2%	**Production Increase Ratio:** 267%. **Effective Period:** > 180 days. Significantly extends treatment longevity compared to conventional methods in the same block.
Case 2	Injection Well; **Casing Leakage with Sustained Annular Pressure**	Digital Twin Simulation & Evaluation, Fiber-Reinforced Composite Material Wrapping Repair	**B-Annulus Pressure:** Sustained Pressure → Zero & Stable **Injection Status:** Restored to designed injection rate and pressure	Confirmed repair success with no recurrence for 12 months. A more economical and efficient solution compared to casing replacement or heavy workover.
Case 3	Production Well; **Scattered Remaining Oil with Severe Interlayer Interference**	Digital Twin Adaptability Evaluation, **Single-Well Injection-Production** Completion String, Dynamic Injection-Production Optimization	**Oil Rate:** 1.8 → 5.2 t/d **Comprehensive Water Cut:** Decreased by ~15 percentage points	Successfully established an internal "injection-production" circulation. Resolves interlayer interference and taps scattered remaining oil efficiently without drilling new wells, demonstrating high economic benefit.

4.1 Case Study 1: Integrated Acidizing and Enhancing System for Low-Pressure, High-Water-Cut Wells

Well A is a production well located in a block where the formation pressure remains at only 65% of normal. The well's daily production decreased from 25.0 m³/d to 8.5 m³/d, while the water cut increased to 92.5%. Diagnosis indicated near-wellbore inorganic scale deposition, particulate migration blockage, and associated emulsion blockage. A digital twin model was used to simulate the injection process of different acid systems, optimizing an integrated acidizing and unblocking system composed of a clay stabilizer, deep slow-release acid, and a demulsifier. The simulation determined the optimal injection rate and dosage, ensuring deep penetration in weak formations without inducing fractures. During field operations, wellhead pressure and pump injection rate were monitored in real time, and the data was fed back to the digital twin model for comparison with the predicted "safe pressure window." Injection parameters were adjusted in real time based on the pressure response to ensure the operation remained within a safe and effective range. Following acidizing, a nanoparticle suspension was injected as a post-treatment fluid to stabilize the microparticles and improve wettability, aiming to extend the effectiveness of the treatment. One month after implementation, the well's daily fluid production recovered to 20.3 m^3/d, daily oil production increased from 0.6 m^3/d to 2.2 m^3/d, and water cut decreased to 89.2%. The oil production increase ratio reached 267%, and the effective period exceeded 180 days, far surpassing the average effective period of 90-120 days for conventional acidizing in this block, demonstrating excellent long-term effectiveness.

4.2 Case Study 2: Systematic Repair of a Well with Casing Leakage under Pressure

Well Condition and Problem Overview: Well B is a water injection well. Pressure was observed in the B annulus. Multi-bore borehole drilling and electromagnetic flaw detection logging confirmed a 3-meter-long deformed section of casing at a depth of 1250m, with multiple leakage points, determined to be caused by formation creep. Based on the geometry of the deformed section and in-situ stress data, a digital twin model was used to simulate the mechanical behavior and sealing effect under different repair methods (such as conventional cementing, expansion tubes, and composite material wrapping). Simulation results showed that fiber-reinforced composite material wrapping repair had better adaptability to irregular deformation and higher post-repair strength; therefore, this method was selected. After wellbore cleaning and pretreatment, a specialized downhole tool string was used to precisely deliver the fiber composite material and curing agent to the target section, and the curing process was monitored in real-time using temperature logging. After repair, the tubing string was pressure tested. Subsequently, injection tests were conducted, and the injection pressure and flow rate data were compared with the digital twin predictions to verify the repair effect.

The annular pressure dropped to zero and remained stable. Injection pressure and volume returned to normal design levels. After 12 months of continuous monitoring, the annular pressure did not rise again, and the injection profile remained stable. Compared to complex and costly operations such as sleeve replacement or milling, this repair achieved its remediation goals with a shorter operation cycle and lower cost, validating the economic and technical advantages of the new process materials.

4.3 Case 3: Same-Well Injection and Production Technology to Tap into Dispersed Residual Oil

Well C is located in an area where residual oil is dispersed vertically. The original well produced three thin layers, with severe inter-layer interference, rapid increase in water cut, and low overall production rate. Traditional layered production requires the installation of multi-stage packers for complex injection and production, which is costly and risky. A same-well injection and production process string was designed by simulating the production of each layer using a digital twin model [11]. The string is equipped with a downhole control device, which can inject water into the well-permeable layer 2 and simultaneously produce the adjacent layers 1 and 3, which are rich in residual oil but have poor permeability. The original string was pulled out, and a new intelligent same-well injection and production string was installed and sealed. Downhole sensors were installed to monitor the injection and production parameters of each layer in real time. The digital twin model was updated regularly based on real-time downhole data and production performance. The water injection rate of layer 2 and the production pressure difference between layers 1 and 3 were simulated and optimized using the model to achieve effective pressure displacement and efficient oil production, and to delay water channeling. After implementation, Well C successfully established an in-well "injection and production" system. Daily oil production increased from 1.8 tons to 5.2 tons, and the overall water cut decreased by 15 percentage points. More importantly, it solved the inter-layer interference problem without adding surface water injection processes or drilling new wells, significantly improving the economics of extracting dispersed residual oil. This case demonstrates the application of intensive and integrated thinking in resolving complex production contradictions.

5. Conclusions and Outlook

5.1 Conclusions

This study addresses the increasingly severe complex downhole problems in the later stages of high water-cut development in old oilfields. Breaking through the limitations of traditional "departmentalized management," it developed and implemented a comprehensive technical system for handling complex downhole problems in old oilfields, centered on "data-driven diagnosis, key technology collaboration, and dynamic optimization decision-making."

Through systematic research and application, a multi-dimensional, high-precision comprehensive diagnostic system for complex downhole problems has been established, breaking through the bottlenecks of traditional diagnostic "information silos" and reliance on experience. By integrating multi-source heterogeneous data and time-series feature engineering, standardized fusion of cross-domain data from geology, engineering, and production has been achieved. Combining supervised and unsupervised machine learning algorithms, a fault classification and early warning model has been constructed, capable of accurately outputting problem types, risk probabilities, and severity levels. Based on a wellbore-formation collaborative digital twin model, in-depth deduction of problem causes and virtual simulation optimization of treatment solutions have been completed, providing scientific "navigation" for subsequent remediation.

An integrated processing technology system covering wellbore repair, reservoir unblocking, and intelligent decision-making has been constructed, realizing an upgrade in the remediation concept from "single repair" to "systemic recovery." With wellbore function restoration as the core, the developed composite material-enhanced repair, adaptive intelligent plugging, and integrated injection and extraction technologies have effectively solved problems such as casing damage, inter-layer/external flow, and dispersed extraction of residual oil, significantly reducing the cost and risk of traditional operations. For reservoir complex blockage issues, the innovative deep-seated synergistic acidizing and physical-chemical combined permeability enhancement technologies have achieved the dual goals of "removing damage" and "reconstructing seepage channels," improving the effectiveness and long-term sustainability of the measures. The dynamic optimization process using big data and digital twins throughout the entire process forms a closed-loop mechanism of "simulation-construction-feedback-iteration," endowing the technology system with the ability to continuously improve itself.

Field application cases have fully validated the effectiveness and universality of the integrated treatment technology system. In three typical wells (low-pressure, high-water-cut composite damage wells, casing leakage wells under pressure, and residual oil dispersion-type interference wells) in a high-water-cut old oilfield in eastern China, the system achieved a 267% increase in oil production, a 12-month recurrence-free casing repair effect, and a 15 percentage point reduction in water cut, respectively. Furthermore, the effective period of the measures was significantly extended compared to traditional technologies, and operating costs were substantially reduced. Practice shows that this system can flexibly adapt to different types of complex downhole problems, demonstrating outstanding advantages in restoring wellbore function, increasing single-well productivity, and optimizing block development benefits.

5.2 Outlook

Although this research has achieved preliminary results, the in-depth development of old oilfields remains an ongoing challenge, and there is still ample room for future research. Future research should incorporate more real-time high-frequency data (such as distributed fiber optic DTS/DAS) and explore unsupervised and semi-supervised learning algorithms to better address the problem of sample scarcity and achieve truly real-time dynamic diagnosis and early warning. Next-generation repair and unblocking materials should develop towards intelligent directions of "self-sensing, self-regulation, and self-repair." Simultaneously, there is an urgent need to develop high-performance, green, and environmentally friendly chemical agents to meet increasingly stringent environmental requirements and reduce the ecological footprint. Current digital twins mostly focus on single wells or local sections. Future research should construct a full life-cycle digital twin system covering multiple scales from "reservoir-well group-single well-tubing," achieving integrated simulation and optimization from macro-level development strategies to micro-level construction parameters, providing a core platform for intelligent oilfield management. To promote the large-scale application of the technology, it is recommended that the research results be further refined into standardized technical guidelines, software modules, and databases. By creating an integrated intelligent decision support platform, the technical barriers to use are lowered, enabling this comprehensive processing system to create value in a wider range of old oilfield blocks.

In short, maintaining stable production in old oilfields is a protracted battle requiring continuous innovation. Adhering to a systems engineering approach that combines geology and engineering, and synergizes technology and economics, with data and intelligence at its core, is the inevitable direction for tapping the potential of old oilfields and ensuring national energy security.

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