

Evaluation and Optimization of a Nitrogen-Assisted Viscosity Reduction Technology in Karamay Heavy Oil Reservoir

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Abstract: To address challenges of rapid production decline and poor recovery in the high-water-cut, high-viscosity, and energy-deficient T2k reservoir of Karamay Oilfield, nitrogen-assisted composite viscosity reducer technology was applied. Based on data from nine wells treated in 2023, this study analyzes the mechanism, effectiveness, and influencing factors. Results show that nitrogen energy enhancement and chemical viscosity reduction synergistically remove near-wellbore blockages, supplement energy, and reduce viscosity, with significant effect in wells having formation depletion <700 mPa·s viscosity, yielding 578 t cumulative and 64 t average incremental oil per well. **Optimization includes:** multi-stage (e.g., three-stage) outperforms single-stage treatment; prepad nitrogen should match perforation thickness, viscosity reducer ≤ 200 m³; post-treatment casing pressure and submergence control are crucial. Typical well analysis summarizes failure causes and proposes refined "one-well-one-strategy" selection and parameter optimization, supporting efficient application in similar high-viscosity reservoirs.

Keywords: Nitrogen Energy Enhancement; Chemical Viscosity Reduction; Blockage Removal; High-Viscosity Reservoir; Effectiveness Evaluation; Treatment Optimization

1. Introduction

As mature oilfields in eastern China enter a late development stage characterized by high water cut and high recovery factor, the economic and effective enhancement of oil recovery and exploitation of hard-to-recover residual oil have become critical challenges for maintaining stable production. The T2k reservoir in the Karamay Oilfield is a typical example, facing a triple contradiction of high recovery factor, high crude oil viscosity, and insufficient natural energy.

Specifically, long-term production has led to severe formation energy depletion and reduced production pressure differential; high crude oil viscosity results in poor fluidity and the formation of organic scale blockages near the wellbore; high comprehensive water cut and low waterflood efficiency contribute to rapid production decline. These factors collectively limit the effectiveness of conventional stimulation methods, creating an urgent need for a composite technology capable of simultaneously replenishing formation energy and improving crude oil mobility. Nitrogen-assisted chemical viscosity reduction technology has been developed to address this need [1-3]. Nitrogen, as an inexpensive, readily available, and inert gas, can effectively supplement formation energy and increase the production pressure differential when injected. Its compressibility aids in driving chemicals deeper into the formation and assists in flowback. Composite viscosity reducers, typically composed of surfactants, significantly reduce oil-water interfacial tension, emulsify or alter the flow characteristics of crude oil, thereby reducing viscosity and removing organic blockages. Theoretically, combining these two can achieve a synergistic "1+1>2" effect [2]. However, the field application effectiveness of this technology is constrained by multiple factors, including geological conditions, operational parameters, and production management, leading to considerable uncertainty. Therefore, this study focuses on nitrogen-assisted viscosity reduction treatments conducted in nine wells in the T2k reservoir in 2023. Through systematic performance evaluation and in-depth case analysis, it aims to: (1) objectively assess the overall effectiveness of the technology; (2) identify key geological and engineering factors influencing treatment outcomes; (3) analyze the underlying causes of typical successful and failed cases; and (4) establish targeted well selection criteria and operational optimization strategies to guide

future precise implementation, thereby improving treatment success rates and economic efficiency.

2. Reservoir Challenges and Treatment Mechanism

2.1 Main Reservoir Challenges

The T2k reservoir faces three key issues, necessitating stimulation measures: *Poor Reservoir and Fluid Properties*: High in-situ crude oil viscosity, with surface degassed oil viscosity (at 20°C) ranging from 191 to 3117 mPa·s, severely impairs fluid mobility and increases flow resistance. *Acute Development Contradictions*:
 o *Energy Deficiency*: Weak natural energy and long-term production have led to low formation pressure maintenance and significant energy depletion.
 o *High Water Cut*: High comprehensive water cut, severe ineffective water cycling, and low waterflood efficiency.
 o *Severe Blockages*: High-viscosity oil and formation fines readily accumulate near the wellbore, forming complex blockages that further reduce flow capacity. *Deteriorating Production Performance*: Characterized by "rapid production decline, low pump submergence, and short production cycles." Wells generally suffer from insufficient fluid supply and low pump efficiency, making stable production difficult.

2.2 Mechanism of Nitrogen-Assisted Viscosity Reduction Technology

This process combines nitrogen energy enhancement with composite chemical viscosity reducer blockage removal [1,2]. Its core mechanism lies in "energy enhancement" and "viscosity reduction": *Energy Enhancement*: Injecting high-pressure nitrogen serves three purposes: 1) Directly supplements formation energy, increasing pressure and expanding the

drainage radius. 2) Utilizes gas compressibility and expansibility to provide continuous drive energy during shut-in and production, promoting fluid flowback. 3) Acts as a "displacing agent," pushing the viscosity reducer deeper into the formation and helping carry back emulsified/dispersed heavy oil and blockages. *Viscosity Reduction & Blockage Removal*: The CY-I agent is a composite of macromolecular surfactants and nano-inorganic production aids. Its mechanism: Surfactants adsorb at the oil-water interface, drastically reducing interfacial tension, enabling crude oil to emulsify/disperse in water, forming low-viscosity oil-in-water emulsions (viscosity reduction >90%) [4]. Nano-inorganic aids may alter rock wettability, inhibit fines migration, and disperse asphaltenes [5]. Together, they effectively dismantle organic scale and complex blockages near the wellbore, restoring and improving oil flow channels [6]. "Energy enhancement" provides the drive and space for "viscosity reduction," while "viscosity reduction" releases the flow potential for "energy enhancement." They work synergistically to increase well productivity and extend production cycles [7].

Figure 1 visually illustrates this synergy in three stages. Stage A (Pre-treatment) depicts the initial state with high-viscosity oil forming organic blockages near the wellbore. Stage B (Nitrogen Injection) shows high-pressure nitrogen injection, where its multi-scale molecules work with the viscosity reducer to supplement energy and drive the chemical. Stage C (Viscosity Reducer Action) demonstrates the final effect: the agent emulsifies the oil, significantly reduces viscosity, and clears flow channels. The figure clearly interprets the core process: "Energy enhancement provides the drive for viscosity reduction, and viscosity reduction releases the potential for energy enhancement."

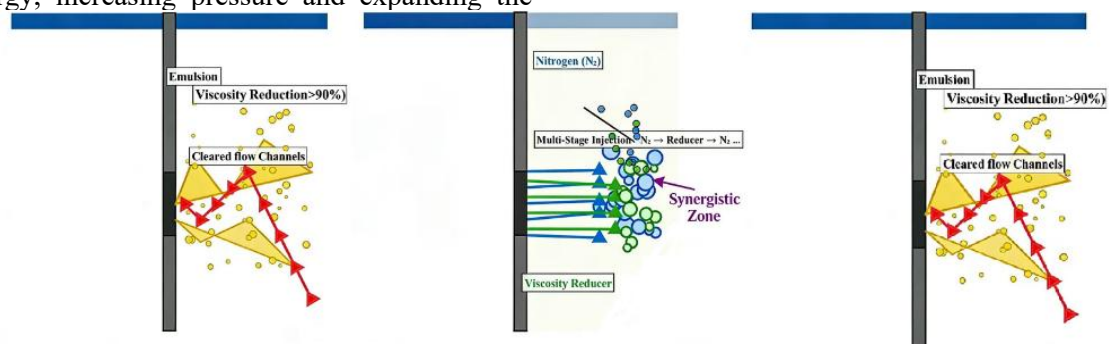


Figure 1. Schematic Diagram of the Three-Stage Mechanism of Nitrogen Energization and Viscosity Reduction Technology

3. Overall Treatment Effectiveness Analysis

In 2023, nitrogen-assisted viscosity reduction treatments were implemented on 9 old wells in the T2k reservoir. As shown in *Table 1*, the effectiveness of these 9 treatments varied significantly. The table summarizes key data for each well, including crude oil viscosity, operational parameters, and incremental oil production, providing a basis for macro-

statistical analysis and preliminary pattern identification. The data indicates a cumulative incremental oil production of 578 tons, with an average of 64 tons per well, resulting in a treatment success rate of 66.7%. From this table, potential correlations between factors such as treatment type (e.g., the three-stage process used in Well TD22), crude oil viscosity, and treatment effectiveness can be preliminarily observed.

Table 1. 2023 Nitrogen-Assisted Viscosity Reduction Treatment Effectiveness Statistics

| Serial Number | Well Number | Viscosity Reducer Dosage (m ³) | N2 Dosage (Nm ³) | Cumulative Oil Increase (t) | Crude Oil Viscosity (20°C,mPa·s) | Construction Process | Effect Evaluation |
|---------------|-------------|--|------------------------------|-----------------------------|----------------------------------|---|----------------------|
| 1 | TD22 | 195 | 15000 | 240 | '491' | Viscosity Reduction + N + Viscosity Reduction | 'Significant' |
| 2 | TD66 | 200 | 12000 | 144 | '552' | Viscosity Reduction + N + Viscosity Reduction | 'Relatively Obvious' |
| 3 | TD11 | 250 | 11500 | 65 | '1103' | N + Viscosity Reduction | 'General' |
| 4 | TD44 | 200 | 10000 | 38 | '757.6' | N + Viscosity Reduction | 'General' |
| 5 | TD88 | 100 | 8120 | 28 | '3117' | N + Viscosity Reduction | 'General' |
| 6 | TD55 | 200 | 10000 | 28 | '333' | N + Viscosity Reduction | 'General' |
| 7 | T20195 | 200 | 3000 | 21 | '590' | N + Viscosity Reduction | 'Poor' |
| 8 | TD33 | '200' | 5000 | 9 | '191' | 'N + Viscosity Reduction' | 'Poor' |
| 9 | TD77 | 200 | 10000 | 5 | '1058' | N + Viscosity Reduction + N + Viscosity Reduction | - |
| Total/Average | 9 Wells | 1845 | 96120 | 578 | - | - | - |
| Mean | - | 205 | 10180 | 64 | | | |

Preliminary Observations: Impact of Process Design: Well TD22, which demonstrated the best results, employed a unique three-stage process alternating between viscosity reducer and nitrogen injections. In contrast, most other wells used conventional single or two-stage processes involving co-injection. This suggests that multi-stage alternating injection may facilitate better contact and interaction between the chemical agent and the reservoir crude oil [8]. Impact of Crude Oil Viscosity: Wells TD77 and TD11, which showed the poorest results, both had crude oil viscosities exceeding 1000 mPa.s. Conversely, the two best-performing wells had viscosities below 600 mPa.s. This indicates that

this treatment process is better suited for medium-to-low viscosity crude oils [3]. Significant Variability in Operational Parameters: Key parameters such as nitrogen injection volume (ranging from 5000 to 15000 Nm³) and viscosity reducer volume (ranging from 100 to 300 m³) showed substantial variation. The lack of standardized parameter design has hindered the comparability and potential for optimization of treatment outcomes [9].

To further reveal the potential relationships between key parameters (such as nitrogen injection volume and crude oil viscosity) and the oil enhancement effect, a visualization analysis was conducted on the data from Table 1, with

the results shown in Figure 2. This figure intuitively illustrates the distribution of measure effectiveness under different parameter

combinations, providing a graphical basis for subsequent parameter optimization.

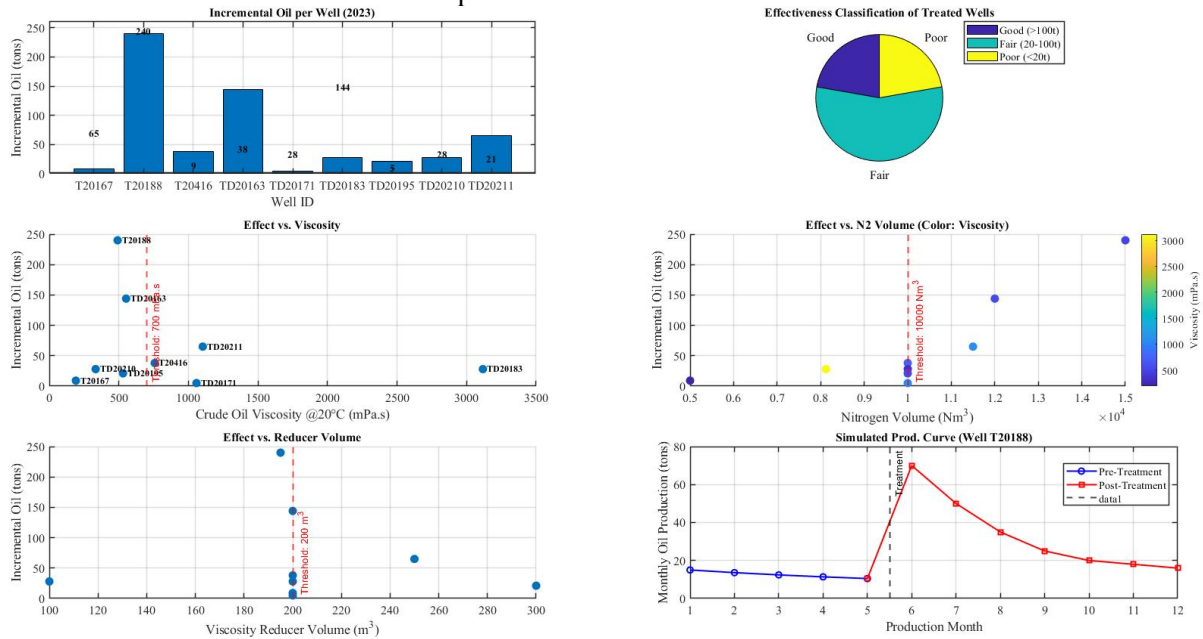


Figure 2. Visualization Analysis Chart of Nitrogen-Assisted Viscosity Reduction Measures Data for 2023

4. In-Depth Analysis of Typical Well Cases and Factors Influencing Effectiveness

To uncover the underlying reasons for treatment success and failure, this section conducts a comparative analysis of representative wells with different outcomes. The production performance comparison curves of these typical

wells are plotted in Figure 3, which provides a visual timeline to analyze the treatment response, peak production timing, decline trends, and effective period duration. This graphical analysis, combined with the detailed case descriptions below, helps to elucidate the complex interplay between geological conditions, operational parameters, and post-treatment management.

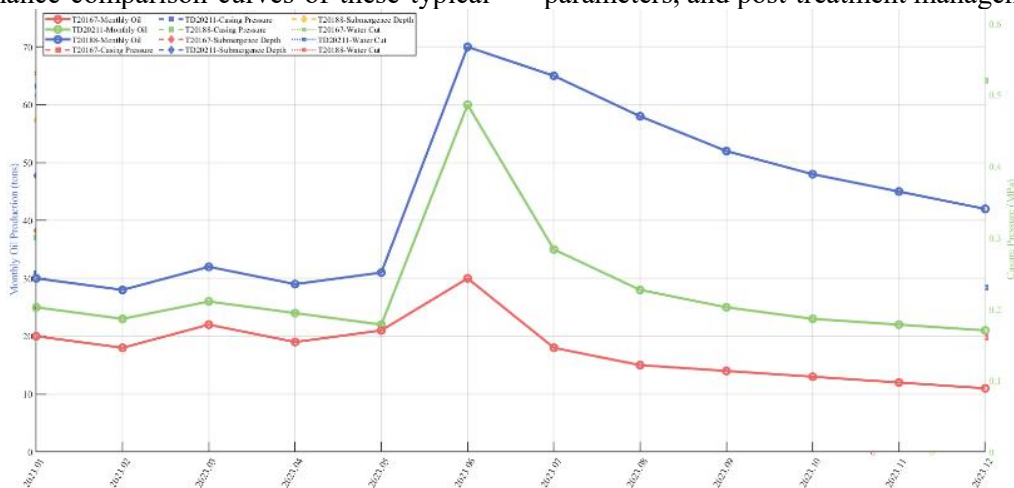


Figure 3. Production Performance Comparison Curves of Typical Wells

4.1 Success Case: Well TD22 (Exemplar of Three-Stage Process)

Well Conditions: Crude oil viscosity: 491 mPa.s; perforated thickness: 13m. Treatment: Employed a three-stage alternating "chemical agent + nitrogen" injection process. Total nitrogen:

15,000 Nm³; Viscosity reducer: 195 m³. Outcome: Monthly oil production surged from a low pre-treatment level to 70 tons post-treatment. Cumulative incremental oil: 240 tons, showing the most significant effect. Success Factors: i. Process Advantage: The three-stage process created a "local viscosity reduction - gas drive -

further reduction - further drive" cycle. Initial viscosity reduction enhanced injectivity, followed by nitrogen driving the treated oil deeper and replenishing energy. The final agent stage treated more distant zones. This improved chemical distribution, extended the effective radius, and sustained energy replenishment [2,7].

ii. Parameter Compatibility: Medium viscosity and favorable reservoir conditions were well-suited to the process. Ample nitrogen injection effectively supplemented reservoir energy [10].

iii. Reasonable Post-Treatment Management: Initial casing pressure and pump submergence were relatively stable post-treatment, ensuring prolonged stable fluid production. While later casing pressure increases shortened the effective period, substantial early production gains were achieved.

4.2 Moderate Success Case: Well TD11 (Limited by High Viscosity & Production Management)

Well Conditions: High crude oil viscosity: 1,103 mPa.s; perforated thickness: 10m. Treatment: Conventional single-stage co-injection ("nitrogen + reducer"). Nitrogen: 11,500 Nm³; Viscosity reducer: 250 m³ (highest volume used). Outcome: Oil production reached 60 tons in the second month, indicating successful near-wellbore cleanup, but dropped sharply by the third month. Cumulative incremental oil: 65 tons, with a short effective period. Limiting Factors:

i. Excessively High Oil Viscosity: The primary constraint [3]. Effective dispersion and deep, lasting action of the reducer in such a viscous medium was difficult.

ii. Contradiction in Reducer Volume vs. Concentration: Despite the largest volume used, a low concentration (0.1%) may have been inadequate for high viscosity. Higher concentration might have been more effective than simply larger volume [4], especially since the large volume prolonged the post-flush period.

iii. Inappropriate Production Management: Improper post-treatment casing pressure control led to critically low pump submergence. For high viscosity wells, sufficient submergence is essential to maintain pumping efficiency and fluid production rate [11]. Low submergence caused slow production, allowing re-blockage of the newly cleared flow channels.

4.3 Failure Case: Well TD33 (Insufficient Energy & Poor Fluid Production)

Well Conditions: Lowest crude oil viscosity: 191

mPa.s; perforated thickness: 10m. Treatment: "Nitrogen + reducer" process, but with the lowest nitrogen volume among all wells: 5,000 Nm³. Outcome: Initial pump submergence increase and oil production to 30 tons in month one, but a sharp decline in month two. Cumulative incremental oil: only 9 tons. Failure Reasons:

i. Severely Insufficient Nitrogen Injection: Volume was 1/3 to 1/2 of other wells. For an energy-depleted well, energy replenishment is fundamental. Inadequate energy supplement limited the increase in drawdown pressure, failing to provide sufficient drive for fluid flow and sustained production [1,10].

ii. Poor Fluid Production Control: A low post-treatment production rate was documented. Given the energy deficit, failure to optimize production parameters (e.g., stroke speed) hindered timely production of the viscosity-reduced oil, preventing consolidation of treatment benefits [11].

4.4 Key Learnings from Other Cases

Wells TD88 & TD44: Both suffered from excessive post-treatment casing pressure control, leading to unstable or low pump submergence, severely impacting pump efficiency and production stability [11]. This highlights the need for precise post-treatment management.

Wells TD55 & TD77: Excessive overflush water volume (~100 m³) can dilute the chemical concentration in the near-wellbore zone, prolong the post-flush period, and potentially lead to cold damage (if water temperature is low) [9].

Well TD99: The high viscosity reducer volume (300 m³) extended the post-flush period excessively, negatively impacting overall treatment efficiency [9].

5. Key Insights and Optimization Recommendations

Based on the overall effectiveness statistics and in-depth analysis of typical well cases, the following key insights and optimization recommendations are summarized.

5.1 Key Insights

Technology Applicability Limits: Nitrogen energization and viscosity reduction technology is highly effective and suitable for promotion in wells where formation depletion is not severe, near-wellbore blockage is caused by viscous oil, and crude oil viscosity (at 20°C) is below 700 mPa.s. For wells with excessively high oil

viscosity (>1000 mPa.s) or extremely severe formation energy depletion, cautious evaluation or combination with other stronger energization measures is required. Critical Role of Operation Process: Multi-stage injection processes (especially the three-stage process) are significantly superior to single-stage slug processes in expanding the effective radius, improving chemical agent utilization, and extending the effective period, and should be prioritized. Scientific Parameter Design: Nitrogen volume must be determined in conjunction with perforated thickness and the degree of formation depletion, supported by quantitative charts. As illustrated in Figure 4, a positive correlation exists between nitrogen injection volume and incremental oil production within a certain range (e.g., up to ~12,000 Nm³), highlighting the necessity of adequate energy supplementation. However, beyond a certain point, the incremental benefit diminishes, indicating an optimal economic and technical dosage window. For medium-viscosity wells, insufficient volume (e.g., <8000 Nm³) is a

primary risk. However, for high-viscosity wells, merely increasing gas volume (e.g., >10000 Nm³) may yield limited results if not matched with a suitable process. Viscosity Reducer Volume and Concentration: Larger volume is not necessarily better; it is recommended to control the volume within 200 m³ (as shown in Figure 4). For high-viscosity wells, priority should be given to increasing agent concentration rather than simply increasing volume. Laboratory experiments are needed to optimize the optimal concentration for different viscosity ranges. The "Second Half" Determines Success: Post-treatment production optimization and dynamic monitoring are equally critical as the operation itself. Proper casing pressure control (maintaining a high pump submergence) and timely adjustments to the liquid drainage schedule are key to consolidating treatment results and extending their effective period. The short effective period in many successfully treated wells is primarily attributed to shortcomings in this phase.

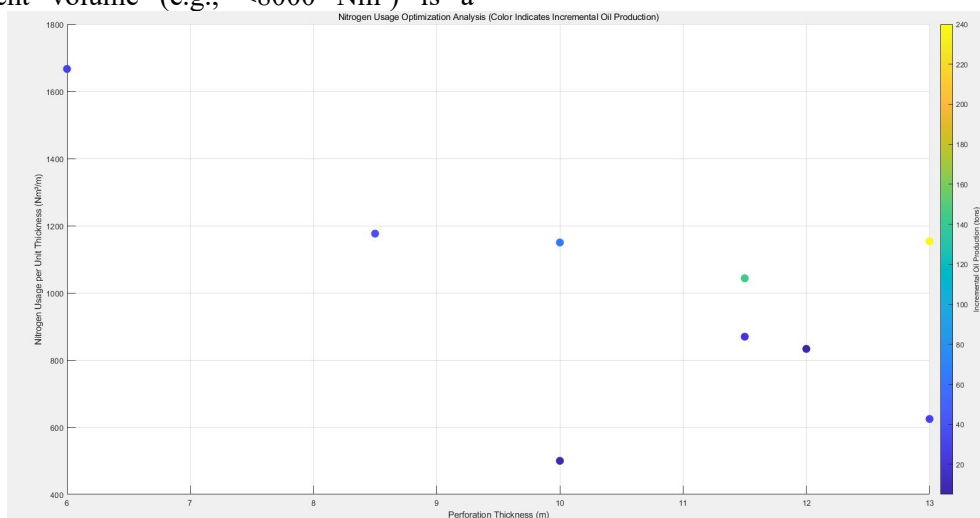


Figure 4. Scatter Plot of the Relationship Between Nitrogen Usage and Incremental Oil Production

5.2 Optimization Strategies and Recommendations

Refined Well Selection: Establish quantitative well selection criteria as shown in Table 2. Prioritize wells meeting the following conditions: (1) Crude oil viscosity (at 20°C) < 700 mPa.s [3]; (2) Relatively well-maintained formation pressure (acceptable energy deficit) [1]; (3) Dynamic analysis indicates near-wellbore blockage as the primary issue [6]; (4) Perforated intervals are relatively concentrated with good permeability. For high and extra-high viscosity

oil wells, pilot laboratory tests and rigorous feasibility studies are required [5].

Optimization of Operation Design: The optimization of operation design should follow the principle of "Process Priority, Parameter Matching" [5,9,10].

Promote Multi-Slug Process: Establish the multi-slug process of alternating "Nitrogen + Viscosity Reducer" injection as the primary recommended process template [2,8]. The number and size of slugs can be fine-tuned based on well conditions [7].

Table 2. Decision Support Data Sheet for 'One-Well-One-Policy' Energization and Viscosity Reduction Treatment

| | Well Name | Crude Viscosity | Perf. Thk. | N2 Volume | Avg. Prod. Rt. | Injection Process | Cost per t | Effect Rank | Case Summary |
|---|-----------|-----------------|------------|-----------|----------------|---|------------|-------------------------------|---|
| 1 | TD11 | 1103 | 10 | 11500 | 250 | Single-Stage (N+Visc.Red.) | 65 | Poor Effect | High viscosity (>700), improper casing pressure control affecting pump efficiency |
| 2 | T22 | 491 | 13 | 15000 | 195 | Three-Stage (Visc.Red.+N+Visc.Red.+N+Visc.Red.) | 240 | Significant Effect | Multi-stage process effective, but late-stage casing pressure high |
| 3 | T33 | 191 | 10 | 5000 | 200 | Single-Stage (N+Visc.Red.) | 9 | Ineffective | Insufficient N2 volume (only 5000Nm ³), low fluid discharge rate |
| 4 | T44 | 757 | 8.5 | 10000 | 200 | Single-Stage (N+Visc.Red.) | 38 | Significant Effect | Parameters reasonable, but late-stage production system affected results |
| 5 | TD55 | 333 | 6 | 10000 | 200 | Single-Stage (N+Visc.Red.) | 28 | Average Effect | Severe depletion, excessive displacement water (>100 m ³) |
| 6 | TD66 | 552 | 11.5 | 12000 | 200 | Two-Stage (N+Visc.Red.+N) | 144 | Relatively Significant Effect | High casing pressure severely affecting submergence depth |
| 7 | TD77 | 1058 | 12 | 10000 | 200 | Two-Stage (N+Visc.Red.+N+Visc.Red.) | 5 | Ineffective | Severe depletion, design parameters too small |
| 8 | TD88 | 3117 | 13 | 8000 | 100 | Single-Stage (N+Visc.Red.) | 28 | Average Effect | Extremely high viscosity, lowest viscosity reducer volume (100m ³) |
| 9 | TD99 | 530 | 11.5 | 10000 | 300 | Single-Stage (N+Visc.Red.) | 21 | Average Effect | Excessive viscosity reducer volume (300m ³), prolonged fluid discharge period |

Combine Standardization with Customization: Develop a chart for calculating nitrogen volume based on core factors such as perforation thickness, crude oil viscosity, and degree of energy deficit [9,10]. Implement an upper limit for viscosity reducer volume (e.g., ≤200 m³) and explore concentration gradient injection modes [4].

Control Displacement Fluid Volume: Strictly limit the volume of displacement water (fresh water). The principle is to displace the chemicals just into the formation, typically not exceeding 50 m³ [9].

Strengthen Operation and Post-Treatment Management:

Avoid Concentrated Operations: Schedule operations reasonably to allow sufficient time for individualized design and post-operation evaluation of each well, achieving closed-loop management of "treat one well, analyze one well, optimize the next."

Implement a "One-Well-One-Policy" Production Regime: Optimize production parameters immediately upon well opening after treatment [11]. The core is controlling casing pressure, ensuring a reasonably high submergence depth, and maintaining pump efficiency. Establish dedicated monitoring files for treated wells, closely tracking key indicators such as liquid production rate, oil production rate, water cut, casing pressure, and submergence depth. Adjust promptly if anomalies occur.

Conduct Systematic Post-Treatment Evaluation:

After treatment concludes, evaluation should not be limited to calculating incremental oil. It must also analyze the effective period and return on investment (ROI), and perform root cause analysis from geological, process, and management perspectives to form a knowledge base that continuously guides technological improvement.

To achieve closed-loop operation and continuous improvement of the aforementioned optimization strategies, an integrated "Geology-Engineering-Management" continuous improvement closed-loop application model, as illustrated in Figure 5, should be established. This model organically integrates three key links: geological problem diagnosis, process optimization design, and production performance management, forming a closed-loop system that includes real-time monitoring, effectiveness evaluation, and feedback-driven optimization. By applying this model, the implementation of the "One-Well-One-Policy" strategy can be systematically supported (e.g., using decision-support data tables similar to Table 2 for well selection and parameter design). Furthermore, it transforms the experience gained from individual well treatments into reusable knowledge, thereby advancing the technology from point-specific applications to systematic, lifecycle-wide optimization. This framework is crucial for ensuring the long-term effectiveness of the treatments.

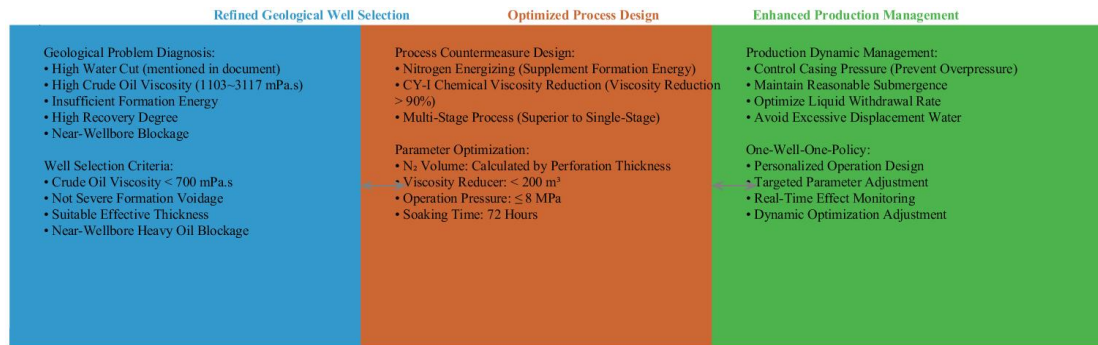


Figure 5. Diagram of the Integrated Geology-Engineering-Management Continuous Improvement Closed-Loop Application Model

6. Conclusions

The nitrogen-assisted composite viscosity reducer energization and blockage removal technology is an effective stimulation method for high-viscosity, low-energy reservoirs such as the T2k in Karamay. Field applications in 2023 confirmed its ability to achieve integrated effects of blockage removal, viscosity reduction, and energy replenishment. The average incremental oil per well was 64 tons, with a treatment success rate of 66.7%.

Treatment effectiveness is jointly controlled by four major factors: reservoir conditions (crude oil viscosity, formation energy), operational processes (slug combination), injection parameters (nitrogen and chemical agent volumes), and post-treatment production strategy (casing pressure and liquid withdrawal control). Among these, excessively high crude oil viscosity (>1000 mPa·s) and an unreasonable post-treatment production strategy are the main causes of treatment failure or short effective periods. The multi-stage injection process demonstrated significant advantages. The alternating cycle of "viscosity reduction - energization" is key to enhancing effectiveness. Operational parameters need to shift from "experience-based" to "scientifically calculated", with particular emphasis on ensuring sufficient nitrogen volume.

Future applications must firmly establish the concepts of "geology-engineering integration" and "operation-management integration." In the early stages, strengthen refined well selection and personalized design; in the later stages, intensify real-time optimization and control of production dynamics to translate technical potential into tangible, sustainable production increase benefits. The understanding and recommendations formed in this study can provide direct references for the optimized

application of this technology in similar reservoirs. In summary, to achieve continuous optimization and efficient application of the technology, an integrated application model of geology-engineering-management, as shown in Figure 5, should be established. This model organically combines three key links: geological problem diagnosis, process optimization design, and production dynamic management, forming a closed-loop system that includes real-time monitoring, effectiveness evaluation, and feedback optimization. This represents a conceptual upgrade from point technology application to full-lifecycle system optimization and is a key framework for ensuring long-term benefits of the treatment.

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