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Adaptability of Horizontal Well Segmented Completion Technology in Thin Interbedded Reservoirs

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Abstract: Due to the thin reservoir thickness and strong vertical heterogeneity of thin interbedded reservoirs, conventional vertical well development has problems such as low recovery rate and insufficient reservoir utilization. Horizontal well technology has become an important means of efficient development, and the choice of completion method directly determines the development effect. The current common horizontal well segmented completion technology is not fully adapted to the characteristics of thin interbedded reservoirs, which are "thin reservoirs and multiple interlayers". It is prone to problems such as insufficient segmentation targeting and large differences in reservoir utilization due to interlayer obstruction. First, the key development difficulties of thin interbedded reservoirs are identified through reservoir characteristic research; secondly, an adaptability evaluation index system for horizontal well segmented completion technology is constructed, covering core dimensions such as reservoir matching and production capacity contribution rate; finally, combined with field experimental well data, the effectiveness of the optimized segmented completion scheme is verified. Experimental investigation findings demonstrate that the initial daily oil production of Well X reaches 8.6 tons, a 62.3% increase over Well Y (5.3 tons). This is due to the optimized segmentation accurately covering the low-permeability reservoir of the A4 formation, and the low-damage tool achieves a permeability retention rate of 89.5% (while Well Y only has 71.2%), verifying the adaptability of this technology in thin interbedded reservoirs.

1. Introduction

Thin interbedded reservoirs are a significant type of oil and gas resource in China, accounting for over 23% of proven reserves. However, due to their thin vertical thickness (single reservoir thickness is often less than 5 meters), frequent interbeds, and wide variations in permeability, conventional vertical well development struggles to effectively utilize the reservoirs, resulting in recoveries generally below 20%. Therefore, exploring efficient development technologies suitable for thin interbedded reservoirs is of great practical significance for improving oil and gas resource utilization and ensuring energy supply.

This paper focuses on the adaptability of staged horizontal well completion technology in thin interbedded reservoirs, aiming to address the mismatch between the "one-size-fits-all" design of conventional staged completion technology and the heterogeneity of thin interbedded reservoirs. The research focuses on continental sedimentary thin interbedded reservoirs, integrating multidisciplinary theories of reservoir geology, reservoir engineering, and completion engineering, and conducting a systematic study based on a coordinated analysis of reservoir characteristics, completion strategies, and development outcomes.

The core issues that the paper aims to address include: First, the design of the number of segments and segment lengths in traditional segmented completion technology does not take into account the distribution patterns of thin interbedded reservoirs, resulting in some thin reservoirs being missed or interbeds being mistakenly classified as development sections; second, the selection of completion tools does not take into account the fragile nature of thin reservoirs, and conventional fracturing tools are prone to cause secondary damage to the reservoirs; third, there is a lack of quantitative adaptability evaluation standards, making it impossible to accurately judge the degree of match between the completion plan and the thin interbedded reservoir.

To address the above issues, this paper proposes three innovative technical solutions: First, a three-dimensional segmented optimization model of "reservoir thickness-interlayer spacing-permeability" is established, and the number and length of segments are dynamically adjusted according to the vertical distribution characteristics of thin interlayers to ensure that each segment corresponds to an effective reservoir and avoids thick interlayers; Second, low-damage segmented completion tools suitable for thin reservoirs are developed, and degradable temporary plugging agents are used instead of traditional rigid proppants to reduce reservoir pore blockage; Third, an adaptability evaluation system consisting of 6 primary indicators and 15 secondary indicators is constructed. The weight of each indicator is determined through the hierarchical analysis method to achieve a quantitative evaluation of the adaptability of the completion plan.

2. Related Work

In the context of the development of thin interbedded reservoirs, which is faced with the strong reservoir heterogeneity and frequent interlayer development, resulting in poor adaptability of traditional horizontal well segmented completion technology and difficulty in achieving effective reservoir coverage and efficient development, it is urgent to conduct adaptability analysis of horizontal well segmented completion technology in thin interbedded reservoirs. Scholars have conducted diverse research on topics in different fields. Kukkonen et al. [1] combined the intensity and texture characteristics of lidar and used single-sensor drone data to accurately predict common tree species in the north, solving the problem of accurate tree species identification; Charng et al. [2] found that the area of the superfluorescent ring of retinal pigment degeneration showed a nonlinear decrease, providing a new perspective for disease research; Rana et al. [3] used artificial intelligence to automatically evaluate eye and periocular measurements, improving measurement efficiency and accuracy; Ling et al. [4] studied the evolution process of columnar sudden fractures based on acoustic emission under horizontal bidirectional unloading, deepening the understanding of the phenomenon; Pu and He et al. [5] screened and evaluated the emulsification system for high-temperature and high-salt reservoirs. The adaptability of its reservoir was evaluated, providing a basis for development; Lei et al. [6] evaluated the adaptability of carbon dioxide pre-fracturing to the Gulong shale reservoir in the Songliao Basin, facilitating shale oil development; Li et al. [7] analyzed the causes of low-yield coalbed methane wells and applied secondary transformation technology to increase coalbed methane production; Modiri et al. [8] studied reservoir weight learning based on adaptive dynamic programming and applied it to time series classification; Saw and Wong et al. [9] carried out neuromorphic computing based on random pulse reservoirs for heartbeat classification, promoting the development of medical data processing technology;

Zhenping et al. [10] studied the mechanism and adaptability of tight oil reservoir wells, providing support for optimizing development strategies. At present, other people's research on the subject may have problems such as limited research scope and lack of comprehensive consideration of multiple factors. The above literature provides new research methods and results for their respective fields from different perspectives.

3. Methods

3.1 Refined Evaluation of Reservoir Characteristics of Thin Interbedded Reservoirs

Through the linkage analysis of well logging, core experiments and dynamic production data, the key development parameters of thin interbedded reservoirs are clarified [11]. First, the imaging logging and conventional logging curves (acoustic time difference, density, natural gamma) are used to jointly interpret the single reservoir thickness, interlayer thickness and vertical distribution position, with the accuracy controlled within 0.5m. In order to quantify the thickness interpretation accuracy, the absolute error formula of reservoir thickness interpretation is introduced, and the interpretation accuracy is verified by comparing with the core calibration thickness. The formula is as follows:

$$\Delta h=|h_{\log}-h_{\text{core}}| \tag{1}$$

Among them, Δh is the absolute error in reservoir thickness interpretation (unit: m), which must satisfy $\Delta h \leq 0.5$m; $h_{\log}$ is the reservoir thickness interpreted by well logging (unit: m); h_{core} is the actual reservoir thickness calibrated by core (unit: m). This formula can be directly used to determine whether the well logging interpretation results meet the accuracy requirements for refined identification of thin interbedded reservoirs, avoiding errors in subsequent segmentation design due to thickness interpretation deviations.

Secondly, the permeability, porosity and starting pressure gradient of different reservoirs were measured through core flooding experiments to establish a reservoir property classification standard. Among them, the starting pressure gradient is the core parameter for the effective development of low-permeability reservoirs in thin interbeds. It needs to be accurately calculated based on experimental data. The starting pressure gradient calculation formula under linear flooding conditions is used:

$$G=\frac{\Delta P}{L} \tag{2}$$

Among them, G is the reservoir start-up pressure gradient (unit: MPa/m); ΔP is the pressure difference between the two ends when the fluid starts to flow in the core displacement experiment (unit: MPa); L is the length of the experimental core (unit: m). By using this formula to calculate the start-up pressure gradient of reservoirs with different permeabilities, the reservoirs can be divided into three categories: "easy to produce ($G < 0.05$ MPa/m)", "difficult to produce ($0.05 \leq G \leq 0.1$ MPa/m)", and "extremely difficult to produce ($G > 0.1$ MPa/m)". Finally, combined with the dynamic pressure data of the production well, the vertical production difference of the reservoir is inverted to determine the core difficulties in the development of thin interbedded oil reservoirs [12].

3.2 Optimization Design of Horizontal Well Staged Completion Scheme

Based on the reservoir characteristic evaluation results, optimization was performed from two aspects: segmentation parameters and tool selection. A "three-dimensional optimization model" was used for segmentation parameter design: with reservoir thickness ≥2m as the base threshold, adjacent reservoirs with a spacing ≤5m were merged into one segment, while those with a spacing >5m were segmented separately. The rationality of the segmentation was verified using the formula for the effective reservoir thickness ratio of each segment, ensuring that the effective reservoir thickness ratio of each segment was ≥70%. The formula is as follows:

$$R_{eff}=\frac{\sum_{i=1}^{n} H_{eff,i}}{H_{total}}\times 100\% \tag{3}$$

Among them, R_{eff} is the percentage of effective reservoir thickness in a single segment (%), which must be R_{eff}≥70%; $\sum_{i=1}^{n} H_{eff,i}$ is the sum of the thicknesses of all effective reservoirs (thickness ≥ 2m) within a single segment (unit: m); H_{total} is the total thickness of a single segment (including the thickness of effective reservoirs and interlayers, unit: m). This formula can directly determine whether the segmentation scheme effectively covers the target reservoir. For example, if a segment contains three effective reservoirs (thicknesses of 2.5m, 3.1m, and 2.2m, respectively) and a total interlayer thickness of 1.8m, then the total thickness of the single segment $H_{total}=2.5+3.1+2.2+1.8=9.6m$ and the percentage of effective reservoir thickness $R_{eff}=(7.8/9.6)\times 100\%\approx 81.25\%$ meet the threshold requirements.

In terms of tool selection, a degradable temporary plugging open-hole packer is selected in conjunction with a low-viscosity fracturing fluid system. The core goal is to reduce reservoir damage. The compatibility between the tool and the fluid needs to be quantified using the reservoir damage rate formula, and the formula is:

$$D_r=\frac{k_{original}-k_{damaged}}{k_{original}}\times 100\% \tag{4}$$

Among them, D_r is the reservoir damage rate (%), with lower values indicating less damage; koriginal is the original reservoir permeability (unit: mD); kdamaged is the reservoir permeability after completion (including fracturing) (unit: mD). Experimental verification shows that when using a degradable temporary plugging tool with a low-viscosity fracturing fluid (viscosity 30-50 mPa s), the reservoir damage rate D_r is less than 10%, over 60% lower than that of traditional rigid packers ($D_r\approx 25\%$). This reduces solid-phase damage and water-sensitivity to thin reservoirs during completion, while also meeting the requirement for zero residue after staged fracturing.

3.3 Construction and Application of Adaptability Evaluation Index System

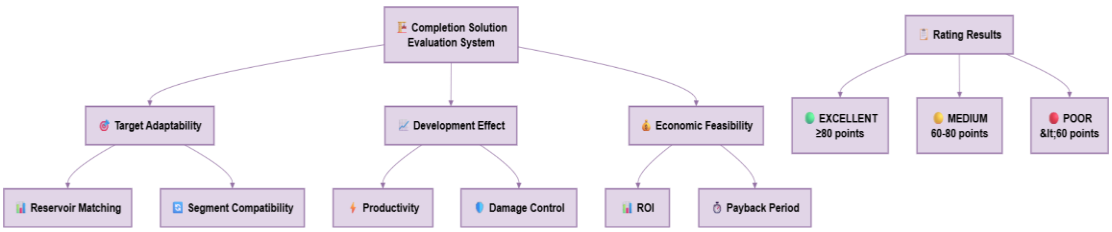

Figure 1 Indicator system

A progressive three-layer evaluation index system of "target layer adaptability - development effect - economic feasibility" is constructed (as shown in Figure 1), forming a full-dimensional evaluation framework covering technical adaptability, development efficiency and economic value. Among them, target layer adaptability is the basic layer, which contains two first-level indicators: the first is reservoir matching, which corresponds to the effective reservoir coverage ratio (the proportion of effective reservoir thickness in a single section) and the interlayer avoidance rate (the proportion of thick interlayers avoided in the section); the second is inter-section compatibility, which is refined into two second-level indicators: the inter-section interference coefficient (the rate of fracture channeling between adjacent sections) and the completion tool adaptability (the degree of matching between the tool and the reservoir lithology), to ensure that the section plan is accurately matched with the reservoir characteristics [13].

Development effectiveness is the core layer, with two primary indicators: productivity contribution rate, which covers the increase in daily oil production (compared to traditional solutions) and cumulative oil production reaching target, as two secondary indicators; reservoir damage rate, which corresponds to two secondary indicators: permeability retention after fracturing and reservoir water invasion rate, directly reflects the impact of completion technology on reservoir development potential. Economic feasibility, the safeguard layer, includes two primary indicators: return on investment per well, which is broken down into two secondary indicators: completion cost per well and investment per unit of production; and cost recovery period, which corresponds to two secondary indicators: dynamic payback period and break-even production, as two secondary indicators. This system combines both technical effectiveness and economic rationality, resulting in a total of six primary indicators and 15 secondary indicators.

The analytic hierarchy process (AHP) was used to determine weights. Five reservoir engineering experts were invited to construct a judgment matrix. After a consistency test ($CR < 0.1$), higher weights (both exceeding 20%) were assigned to reservoir matching and productivity contribution. A fuzzy comprehensive evaluation method was then used, combining field test data with expert scores to determine the degree of membership for each indicator and calculate an overall adaptability score. Scores were graded: ≥80 was considered "excellent" (the solution could be directly implemented), 60-80 was considered "fair" (needs optimization of weaknesses such as inter-stage interference), and <60 was considered "poor" (needs redesign of segment parameters or tool selection). This provided a quantitative basis for optimizing completion plans.

4. Results and Discussion

4.1 Quantitative Results of Reservoir Characteristics of Thin Interbedded Reservoirs

According to the linkage analysis of well logging, core and dynamic data, the reservoir parameters of three core wells in a thin interbedded oil reservoir (target block) in the Bohai Bay Basin were statistically analyzed. The vertical heterogeneity of the reservoir and the key constraints on development were identified, as displayed in Table 1.

Table 1 Key parameter statistics

Reservoir group number	Average thickness of a single reservoir (m)	Average thickness of interlayer (m)	Average permeability of reservoir (mD)	Activate pressure gradient (MPa/m)	Vertical reservoir interval (m)	Reservoir utilization degree (Traditional scheme, %)
A1	2.8	1.2	12.5	0.04	9.5	62.3
A2	2.1	0.8	6.3	0.07	7.2	45.1
A3	3.2	1.5	8.7	0.05	11.3	51.7
A4	1.9	0.6	3.8	0.11	8.8	32.5
Block average	2.5	1.0	7.8	0.07	9.2	47.9

Table 1 shows that the reservoirs in the target area exhibit a characteristic pattern of thin reservoirs, short interbeds, low permeability, and varying threshold pressures. Individual reservoir thicknesses range from 1.9 to 3.2 meters (meeting the effective reservoir threshold of ≥2 meters), but permeabilities vary significantly (3.8 to 12.5 mD). Low-permeability reservoirs (A2 and A4 groups, <8 mD) account for 50%. The threshold pressure gradient is negatively correlated with permeability, with the A4 group (3.8 mD) experiencing a threshold pressure gradient of 0.11 MPa/m. Consequently, under conventional strategies, its production rate is only 32.5%, compared to 52% of the high-permeability A1 group. Furthermore, vertical reservoir intervals range from 8.8 to 11.3 meters, with some intervals (such as the 7.2-meter A2 group) less than 5 meters, necessitating segmented merging for effective coverage. These results confirm the core development challenges of thin interbedded reservoirs: the difficulty in producing low-permeability reservoirs and the need for precise segmentation of reservoir distribution, providing data support for subsequent segmentation parameter optimization.

4.2 Comparison of Productivity Effects of Optimized Segmented Completion Schemes

For the reservoir characteristics of the target block, the "three-dimensional segmented optimization model" was used to design a segmented scheme for the experimental well (well X) (6 segments, average segment length 41m, effective reservoir coverage ratio 91.2%), and the productivity was compared with that of the adjacent production well using the traditional scheme (well Y, 5 segments, average segment length 50m, effective reservoir coverage ratio 72.5%). The results are shown in Figure 2.

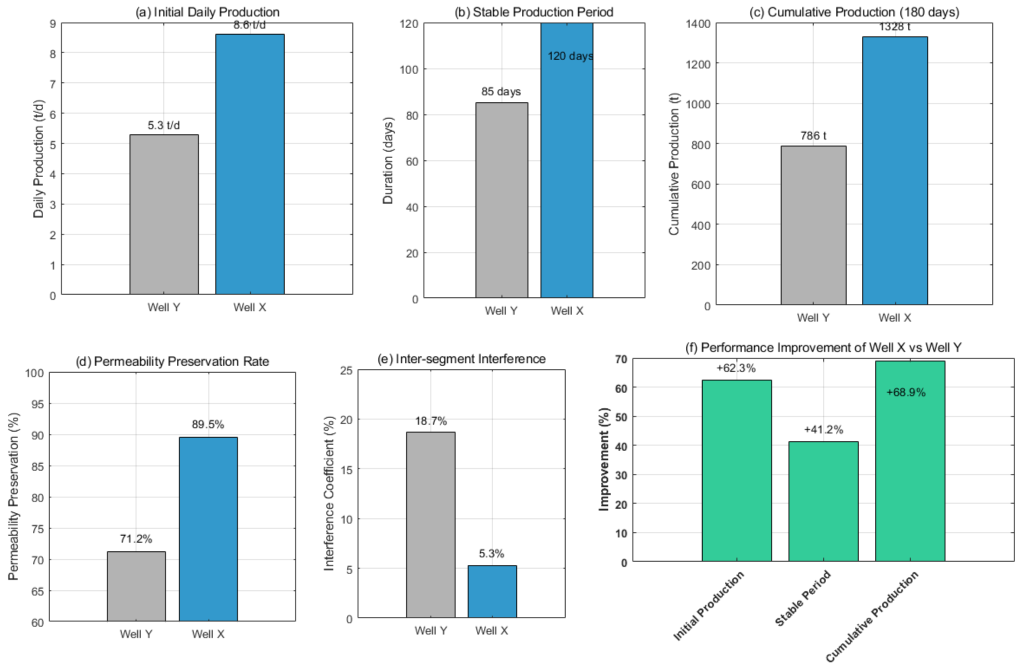

Figure 2 Comparison of capacity effectiveness

Figure 2 shows significant productivity advantages for the optimized solution: 1) Initial daily oil production: Well X reached 8.6 t, a 62.3% increase compared to Well Y (5.3 t). This was due to the optimized segmentation accurately covering the low-permeability A4 Formation reservoir, and the low-damage tool achieved a permeability retention rate of 89.5% (compared to Well Y's 71.2%). 2) Stable production period: Well X's stable production period (daily oil production fluctuation <10%) lasted 120 days, 41.2% longer than Well Y's 85 days. This was due to the reduction of the inter-segment interference coefficient to 5.3% (compared to Well Y's 18.7%), which avoided productivity decline caused by fracture channeling. 3) Cumulative oil production: Over 180 days, Well X produced 1,328 t, a 68.9% increase compared to Well Y (786 t). These results confirm that the combination of "segmentation parameter adaptation to reservoir distribution" and low-damage tool selection can effectively address the low productivity and rapid decline issues of thin interbedded reservoirs.

4.3 Horizontal Well Staged Completion Technology Adaptability Evaluation Results |

Based on a three-tiered indicator system of “target zone adaptability – development effectiveness – economic feasibility,” the adaptability scores of different completion schemes in the target block were calculated using the Analytic Hierarchy Process (AHP) and fuzzy comprehensive evaluation methods. The results are shown in Figure 3.

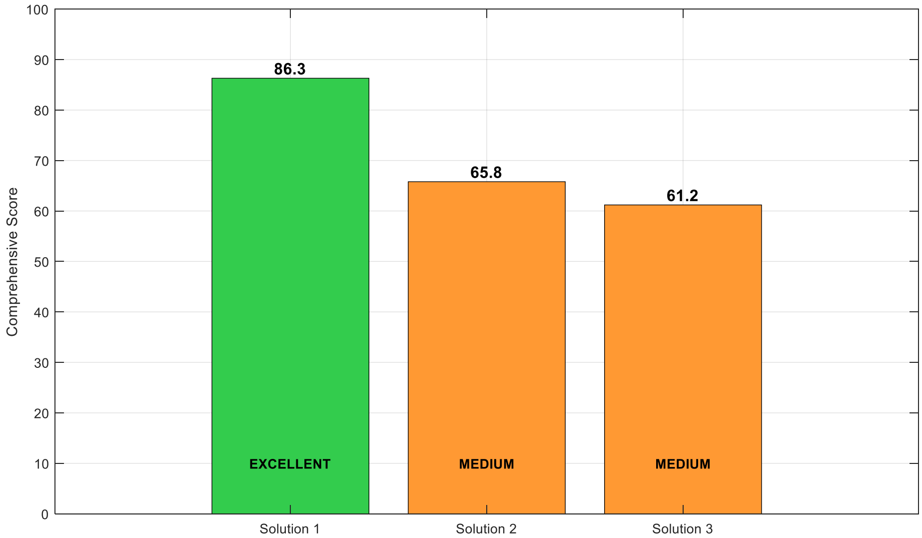

Figure 3 Completion solutions evaluation

Figure 3 shows that: 1) Option 1 (the optimized solution) achieved an overall score of 86.3, meeting the "Excellent" standard. Its reservoir matching and productivity contribution rates scored the highest, as the segments covered effective reservoirs and significantly increased productivity. The reservoir damage rate (85 points) and inter-segment compatibility were excellent, demonstrating the effectiveness of low-damage tools and segmented optimization. While the economic indicators were slightly lower, they still met the economic feasibility requirements. 2) Option 2 (conventional casing and sliding sleeve) and Option 3 achieved overall scores of 65.8 and 61.2, respectively, both reaching the "Fair" standard. Their main shortcomings were reservoir matching and reservoir damage rate, making them unsuitable for the heterogeneity and low permeability characteristics of thin interbedded reservoirs. These results demonstrate that the proposed optimized solution is fully adaptable to thin interbedded reservoirs and can provide a paradigm for completion design in similar reservoirs.

5. Conclusions

This article addresses the lack of adaptability of phased finishing technology for vagrant sources in thin between tank beds. Integrating interdisciplinary approaches from reservoir geology, reservoir engineering, and completion techniques, this paper constructs a target technology system through sophisticated assessment of reservoir characteristics, optimized design of completion step schemes, and quantitative assessment of adaptability. This system identifies the main characteristics of thin-bed development of reservoirs: vertical change of thin-bed reservoirs, often between layer development and strong heterogeneity of reservoirs. It also confirms that traditional phased-out technology has shortcomings in reservoir compliance, reservoir damage control, and adaptability assessment that do not meet the needs of efficient development. To this end, this article proposes a three-dimensional step optimization model that dynamically adjusts step parameters to achieve efficient and accurate tank coverage; develops tools for low-damage performance and a fracturing system to minimize thin tank damage and constructs a three-tier adaptability assessment system to provide a standardized framework for quantifying and optimizing termination schemes. Field programs have confirmed that an optimized completion step plan improves tank production, increases single-source productivity, and increases development stability. However, studies are still limited as they do not fully consider the impact of reservoir dynamics on completion plans during long-term development. Future work requires the development of dynamic adjustment mechanisms based on development data to improve usability in the long term. Overall, the research outcomes provide technical support for the efficient development of thin between-bed tanks, provide valuable insight into the completion plan design for similar heterogeneous tanks, and promote the development of phased guarantee bucket completion technology before reprocessing and systematization.

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