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An Evaluation of the Applicability of the Steady-State Productivity Approach for Horizontal Wells in Low-Permeability Heterogeneous Gas Reservoirs

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Abstract: The heterogeneity and complexity of low-permeability oil and gas reservoirs pose significant technical challenges for their efficient development, including reservoir plugging, high flow resistance, and optimal well type design issues. These challenges result in high development costs and extended production cycles due to insufficient productivity of oil and gas wells. Therefore, accurately assessing the applicability of horizontal wells and their design parameters in the development of low-permeability reservoirs through oil and gas well productivity prediction has become a pressing key issue that needs to be addressed. In this study, based on the principle of well type optimization in the development of low-permeability oil and gas reservoirs, the adaptability of horizontal wells is evaluated using steady-state productivity methods, and their stimulation effects are predicted and analyzed. A systematic comparison of the steady-state productivity of horizontal wells and vertical wells is conducted, productivity predictions for different types of gas reservoirs are conducted, the design parameters of horizontal wells (highly deviated wells) are optimized, and a well type adaptability evaluation system suitable for different reservoir characteristics is formed. The research findings indicate that vertical wells are preferable for gas wells when the steady-state productivity ratio (HRV) is less than 1. However, when the HRV is greater than or equal to 1, the benefits of horizontal and highly deviated wells become notably superior to those of vertical wells. Taking into account the output value, cost, and net income of the gas well, the optimal outcome is achieved with a horizontal section length of 800 m. Ultra-low-permeability thick reservoirs are best suited to vertical wells, low-permeability thick reservoirs to highly deviated wells, and low-permeability thin reservoirs to horizontal wells. The assessment of steady-state productivity offers a theoretical foundation for optimizing development plans in low-permeability oil and gas reservoirs.

Keywords: low-permeability gas reservoir; horizontal well; steady-state productivity; well type optimization; stimulation effect prediction

Academic Editor: Qingbang Meng

Received: 12 December 2024
Revised: 2 January 2025
Accepted: 7 January 2025
Published: 9 January 2025

Citation: Zhang, H.; Cheng, J.; Zhang, X.; Miao, Y.; Jiang, H.; Yu, B.; Meng, L. An Evaluation of the Applicability of the Steady-State Productivity Approach for Horizontal Wells in Low-Permeability Heterogeneous Gas Reservoirs. *Processes* **2025**, *13*, 173. https://doi.org/10.3390/pr13010173

1. Introduction

As the impact of fossil fuels on human life continues to grow, the remaining oil and gas resources in conventional reservoirs are steadily decreasing [1,2]. Consequently, low-permeability reservoirs are receiving increasing attention and research [3]. Low-permeability reservoirs, which are globally widespread, have been discovered and explored in numerous countries. These reservoirs typically exhibit three key characteristics: low abundance, low pressure, and low productivity, which present significant challenges for their effective development [4]. The pressing issue that needs to be addressed is how to efficiently extract oil and gas from low-permeability reservoirs. Currently, horizontal well technology is frequently employed to enhance productivity and optimize extraction efficiency, thereby maximizing resource recovery while minimizing drilling and development costs [5–7]. Exploiting low-permeability reservoirs using horizontal wells can effectively address the challenge of achieving favorable economic benefits that is encountered when developing such reservoirs with vertical wells. Based on a productivity formula for horizontal wells that incorporates wellbore friction, we analyze the factors influencing oil well productivity under various conditions, and apply this analysis to the initial development and production allocation of low-permeability reservoirs. Through numerical simulation for production modeling, we ultimately perform an economic evaluation, which provides significant guidance for the efficient development of low-permeability reservoirs.

The development of horizontal well technology exhibits the following key characteristics. Firstly, it exhibits multidisciplinary integration, grounded in the study of oil and gas field geology and reservoir engineering. From an economic perspective, it enhances the technical proficiency of drilling, completion, and oil extraction, while reducing drilling costs. Additionally, it emphasizes reservoir protection by minimizing damage caused by drilling fluids to the reservoir. In the future, with advancements in reservoir prediction technology, fine modeling techniques, and horizontal well drilling and completion methods, we will progressively explore large-displacement horizontal wells and multi-lateral horizontal wells. We will also actively promote large-scale clustered horizontal well groups and factory-style operations. By continuously optimizing the quantity, method, and scale of multi-level transformations in the horizontal section, we aim to further enhance the development efficiency of horizontal wells.

Given the complex conditions of low-permeability oil and gas reservoirs, traditional methods that rely solely on single-factor analysis of horizontal well productivity are inadequate for providing a comprehensive quantitative evaluation and prediction of horizontal well stimulation effects. Consequently, it is challenging to develop an accurate understanding of the suitable conditions for horizontal wells in such specialized reservoirs. The technology for evaluating the suitability of horizontal wells and predicting their stimulation effects primarily involves analyzing and predicting the steady-state and unsteady-state productivity ratios relative to vertical wells, as well as assessing their wellbore liquid carrying capacity [8,9]. This provides theoretical support and practical analysis methods for accurately determining the adaptability of horizontal wells, optimizing the length of horizontal sections, and other particular issues. The solution of the productivity equation for steady-state flow is the simplest way of predicting the oil production capacity of horizontal wells, and is also the most frequently utilized method for dynamic analysis in oilfield production. Numerous researchers have carried out extensive work on solving the productivity equation for steady-state flow [10,11]. The direct derivation and calculation of analytical models are extremely challenging, so many scholars adopt semi-analytical methods for calculations [12,13]. The concept behind the semi-analytical model is to divide the well trajectory into several segments, couple formation flow and wellbore flow within each segment, and fully take into account the effects of friction pressure drop, acceleration pressure drop, and gravity pressure drop.

The research methods for evaluating the productivity of horizontal wells typically include simulation methods and analytical methods [14–16]. Simulation methods utilize principles such as conformal transformation, mapping mirroring, and potential superposition to conduct various transformations, thereby deriving productivity formulas. Analytical methods, on the contrary, commence with mathematical models, and derive particular expressions for the productivity of single-phase-flow horizontal wells by setting particular hypothetical conditions and simplifying initial conditions in the equations. Similar operations are also applied to multi-phase flow. Among simulation methods, physical simulation employs physical models to visually simulate the seepage field of horizontal wells, providing a foundation for mathematical models in scientific research. Notable examples include the Giger method and the Joshi method. Another approach involves the numerical simulation of gas–liquid two-phase or single-phase flow, focusing on the dynamic relationships of fluids inside horizontal wells. Many scholars have carried out research on the productivity of low-permeability horizontal wells. Zhang et al. put forward a calculation formula for the productivity of horizontal wells, laying a foundation for subsequent related research [17]. Giger et al. utilized electrical simulation methods to explore the applicable productivity formula for horizontal wells, considering reservoir anisotropy [18]. Joshi regarded the fluid flow around the horizontal well as an ellipsoid, and studied the steady-state productivity of the horizontal well [19]. Babu et al. took into account the unsteady-state flow conditions of reservoir fluids, and proposed a practical productivity formula for horizontal wells [20]. Alan et al. constructed a single-phase steady-state turbulence model, considering the interior of the horizontal wellbore [21]. Yu et al. established a semi-analytical model with dimensionless Reynolds number, well conductivity, and flow distribution as variables [22]. Kamel et al. proposed a model that combines Darcy's law, a continuity equation, and an energy equation, and covers the factors affecting friction, gravity, acceleration, and fluid flow [23]. Many scholars are committed to studying the productivity formulas of horizontal wells under different geological conditions and their application in actual circumstances, and have derived new productivity formulas through modification and derivation to make them applicable to calculating the productivity of horizontal wells in different environments [24–26]. Li et al. [27] employed numerical simulation methods to optimize different well patterns, and explored the development effects of low-permeability reservoirs under various well patterns. Wang et al. investigated the development effects of staggered well patterns of horizontal wells in low-permeability reservoirs using potential flow theory [28]. Wu et al. derived productivity formulas and analyzed influencing factors for low-permeability reservoirs, considering starting pressure gradients by using different well patterns [29]. Blasingame et al. researched the well pattern forms of horizontal wells in low-permeability reservoirs [30]. Wang et al. derived productivity formulas for horizontal wells with regular well patterns, staggered well patterns, and rhombic inverted nine-spot well patterns [31]. Liu Yuetian et al. took reservoir anisotropy into consideration and researched the optimal arrangement plan for developing low-permeability reservoirs with horizontal wells [32].

The development of low-permeability reservoirs using horizontal well technology is feasible to a certain extent, and represents a promising approach for the efficient exploitation of such reservoirs. However, in extremely low-permeability reservoirs, the investment risk associated with horizontal well projects remains significantly high. Considering the current application status of horizontal wells in China, developing low-permeability reservoirs using horizontal wells remains a relatively feasible option. However, the complex geological structure of these reservoirs and the generally poor petrophysical properties of the rocks impose significant limitations on the implementation of horizontal wells.

Horizontal well technology encounters several disadvantages and challenges in the development of low-permeability oil and gas reservoirs. Firstly, the drilling costs for horizontal wells are significantly higher. The complex trajectory of the wellbore necessitates the use of specialized drilling tools and techniques, which substantially increases construction complexity and associated expenses. Moreover, horizontal wells often suffer from poor wellbore stability, leading to issues such as collapse and mud loss, further complicating the drilling process and increasing costs. Secondly, predicting the productivity of horizontal wells is particularly challenging. The productivity of horizontal wells is influenced by multiple factors, including formation rhythmicity, contamination coefficients, and anisotropic permeability. These factors make it a complex task to accurately forecast productivity in actual production scenarios. Especially in low-permeability, high-temperature, high-pressure, and low-differential-pressure reservoirs, the prediction of horizontal well productivity becomes even more difficult.

To accurately evaluate the applicability of horizontal wells and their design parameters in the development of low-permeability oil and gas reservoirs, we use the steady-state productivity method to form an overall quantitative description of stimulation effects through contour maps and rapid prediction relationships. Considering the heterogeneity of the reservoir and the non-steady-state productivity characteristics of gas wells with limited reserves, we quantitatively evaluate the non-steady-state productivity ratio of horizontal wells relative to vertical wells, based on the analytical solution of a single well's constant production model under non-steady-state percolation conditions. We systematically compare the steady-state productivity of horizontal and vertical wells, predict the productivity of horizontal wells for various types of gas reservoirs, optimize the design parameters of horizontal wells (highly deviated wells), and establish a well type adaptability evaluation system tailored to different reservoir characteristics. This provides a theoretical basis for optimizing the development plans of low-permeability oil and gas reservoirs.

2. Materials and Methods

2.1. Principle of Optimal Selection of Well Patterns

Horizontal wells have development advantages in terms of enhancing the productivity of oil and gas wells and delaying water intrusion in water-bearing oil and gas reservoirs. The optimization of well types has become a priority consideration in the deployment of well networks for oil and gas reservoir development [33]. Mechanism research has analyzed the factors influencing the increase in production ratio of horizontal wells and highly deviated wells compared to vertical wells from the perspective of oil and gas reservoir engineering. However, well type optimization is not only within the scope of oil and gas reservoir engineering research, but it is also a scientific technology that requires comprehensive consideration of factors such as oil and gas reservoir engineering, drilling technology, and economic benefits [34,35].

From the perspective of oil and gas reservoir engineering, the criterion for optimizing well type selection is effectively enhancing the productivity of oil and gas wells. From the perspective of drilling technology, the criterion is meeting the requirements of existing process technologies. From an economic standpoint, the criterion is ensuring economically viable extraction. Only by simultaneously satisfying the requirements of oil and gas reservoir engineering, drilling technology, and economic benefits can a scientifically sound and reasonable well type be selected for oil and gas reservoir development.

Based on the guiding principles of well type optimization criteria, a technical process for well type optimization has been established. Through research on drilling technologies for special well types (primarily horizontal wells and highly deviated wells), it is understood that from the perspective of drilling technology, there are no particular restrictions or additional requirements for the application of these technologies. Provided that reservoir engineering and economic evaluations demonstrate the necessity of employing specialized drilling technologies, existing drilling techniques can be effectively implemented. Therefore, the well type optimization process can be streamlined to focus on reservoir engineering and economic evaluation, with the ultimate aim of enhancing production efficiency.

The principles for optimizing well types in the development of low-permeability oil and gas reservoirs are primarily based on comprehensive evaluations of geological conditions, development outcomes, and technical and economic factors. The unique optimization principles are as follows.

Select appropriate well types based on geological conditions: Evaluate factors such as geological structure, lithology, thickness, permeability, and paleogeographic conditions. For areas with relatively high permeability and simple formation conditions, conventional well types can be utilized. In contrast, for areas with extremely low permeability and complex formation conditions, priority should be given to specialized well types, such as horizontal wells, to enhance oil and gas recovery efficiency [36,37].

Comprehensively consider development outcomes and technical and economic factors: When selecting well types, comprehensively assess the oil production efficiency, stable production capacity, initial investment costs, and operational and maintenance expenses of different well types. For example, although horizontal wells entail higher initial investments, they significantly improve oil production efficiency, facilitating long-term stable production and increasing ultimate recovery rates. Therefore, under economically viable conditions, it is recommended to prioritize horizontal wells for development.

For general low-permeability reservoirs with a permeability greater than 0.01 mD, conventional water injection development can generally meet the requirements for effective exploitation. To further enhance development efficiency, supplementary measures such as small-scale fracturing, horizontal well development, or carbon dioxide flooding can be employed [38,39]. For ultra-low-permeability and ultra-tight oil reservoirs with a permeability less than 0.01 mD, due to more complex formation conditions, advanced technologies like long-horizontal multi-stage fracturing and multi-stage large-scale fracturing in vertical-inclined wells are required in order to achieve economically viable scale development [40,41].

In summary, the optimization of well types for low-permeability oil and gas reservoir development should comprehensively consider factors such as geological conditions, development effectiveness, and technical and economic feasibility. Based on unique circumstances, the most appropriate well type should be selected for optimal development.

2.2. Technical Process for Optimizing Well Patterns

The well selection technology flow, designed in accordance with the well selection criteria (as shown in Figure 1), aims to systematically determine the most appropriate well type for unique geological conditions and development objectives. This approach seeks to maximize the economic benefits and resource utilization efficiency of gas wells. In particular, the process initially evaluates whether a high-angle well or a horizontal well is more suitable, based on the steady-state production ratio of the gas well. For high-angle wells, the inclination angle is further optimized; for horizontal wells, the length of the horizontal section is refined. Finally, the process integrates the net revenue value and controlled reserves of the gas well, to comprehensively optimize the relevant parameters for both high-angle and horizontal wells.

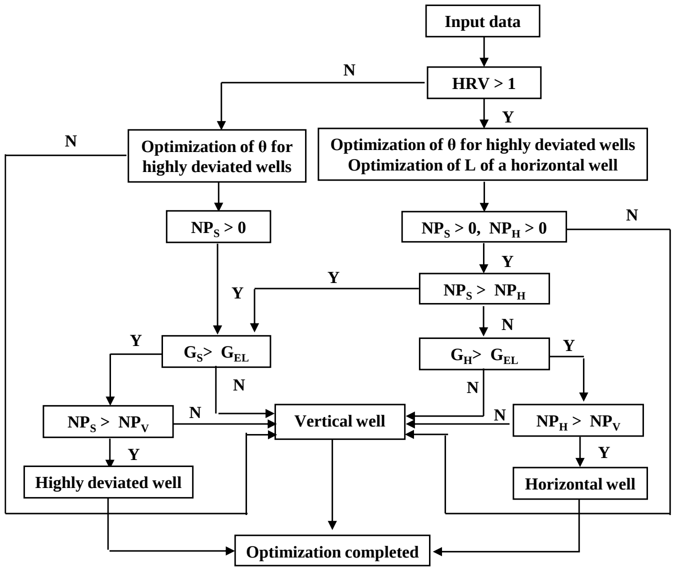

Figure 1. Flowchart of well type optimization techniques in oil and gas reservoir development.

HRV—steady-state productivity ratio of horizontal wells compared to vertical wells. θ—deviation angle of highly deviated well, °. L—length of horizontal segment, m. NP—net income from oil and gas wells, dollars. G—controlled reserves of oil and gas wells, 10^8 m^3. C—development cost of oil and gas wells, 10^4 dollars. The subscript H represents a horizontal well, the subscript S represents a highly deviated well, and the subscript V represents a vertical well.

3. Results and Analysis

3.1. Determination of Steady-State Productivity Ratio of Horizontal Wells

The analysis chart of the steady-state productivity ratio of horizontal wells in comparison with vertical wells reveals that horizontal wells do not necessarily enhance the production of oil and gas wells under all circumstances. For reservoirs with permeability anisotropy characteristics, the productivity ratio of thick reservoirs with short horizontal wells is lower than that of vertical wells under the same conditions, indicating the presence of an area with a steady-state productivity ratio less than 1 in the upper left corner of the chart for the steady-state productivity ratio of horizontal wells. When the horizontal permeability decreases or the permeability anisotropy coefficient increases, the extent of this area expands. Clearly, for cases where the steady-state productivity ratio of horizontal wells is less than or equal to 1 (HRV $\leq$ 1), it is not appropriate to employ horizontal wells for production. Overall, the limitations of applying horizontal wells to thick reservoirs need to be largely compensated for by extending the length of the horizontal section [42].

3.2. Optimization of Parameters for Horizontal Wells (Highly Deviated Wells)

3.2.1. Scenario 1: HRV > 1

The steady-state productivity ratio of highly deviated wells in relation to vertical wells is invariably greater than 1. When the steady-state productivity ratio of horizontal wells in relation to vertical wells is also greater than 1, a comparison between horizontal wells and highly deviated wells becomes necessary. For a target block that is about to undergo well type optimization, its geological conditions are pre-determined. Nevertheless, the key factors influencing the productivity of oil and gas wells—the length (L) of the horizontal section of the horizontal well and the deviation angle (θ) of the highly deviated well—are variable, and can be planned in advance. Therefore, to assess the productivity of horizontal wells and highly deviated wells, it is essential to first complete the optimal design of horizontal wells and highly deviated wells.

The method of optimizing the length of the horizontal section mainly relies on determining the influence of the friction resistance of the horizontal wellbore on the production capacity; by analyzing the changes in friction resistance under different lengths, a curve of the relationship between the length of the horizontal section and the production capacity (Figure 2) can be drawn to determine the optimal length. However, whether a horizontal well is better than a vertical well depends not only on the increase in production, but also on its economic benefits.

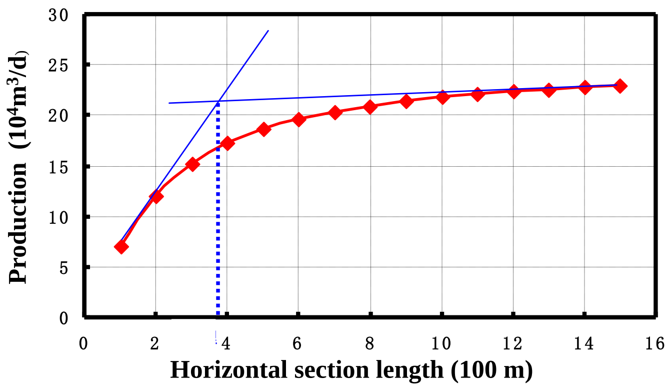

Figure 2. The method for determining the reasonable length of the horizontal section, based on the relationship curve between the length of the horizontal section and production.

In order to comprehensively evaluate the economic benefits of horizontal wells, a systematic parameter optimization method was established under the guidance of the principle of enhanced economic benefits, with the core goal of maximizing economic benefits, by comprehensively considering various factors to ensure that the selected parameters could not only improve production, but also enhance economic benefits.

Economic Benefit Assessment

(1) Production and economic benefits

Production capacity is one of the most important indicators for evaluating economic benefits, but drilling, production, and maintenance costs and net revenue must also be taken into account. For example, although a longer horizontal section can increase production, it may reduce overall economic benefits due to high costs.

(2) Comparison of horizontal wells and vertical wells

Vertical wells are easy to construct and have low costs, but their recovery rates are lower in certain geological conditions; horizontal wells have higher initial investment, but can significantly improve recovery rates in complex geological conditions (such as low-permeability or thick reservoirs), bringing higher long-term economic benefits. The choice should be based on unique geological conditions and economic feasibility.

Parameter Optimization Method

(1) Optimization goal

The goal is to maximize economic benefits by calculating the net revenue at different lengths (or inclination angles) of the horizontal section, and finding the length (or angle) that yields the maximum net revenue as the optimization result (Figure 3).

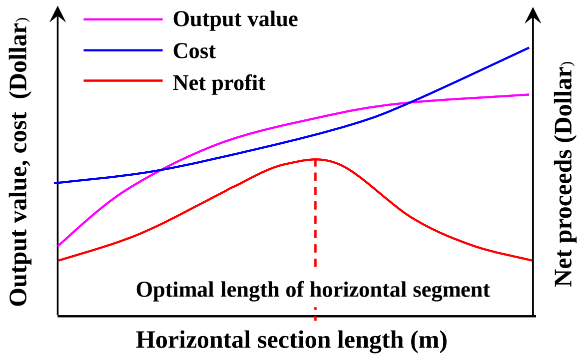

Figure 3. Schematic diagram of horizontal segment length optimization.

(2) Consideration of multiple factors

The optimization process needs to consider the influence of the length of the horizontal section on production capacity, as well as geological conditions, drilling technology, and equipment performance. For example, in low-permeability reservoirs, a longer horizontal section can improve recovery rates. Choosing the appropriate length of horizontal section in high permeability reservoirs requires comprehensive consideration of economic benefits and technical feasibility.

Concerning the optimization of the horizontal segment length, the majority of existing approaches are based on the influence of horizontal wellbore friction on the productivity of horizontal wells. They rely on the relationship curve between the horizontal segment length and the productivity of horizontal wells to determine the optimal length (Figure 2). However, the superiority of horizontal wells over vertical wells does not merely depend on whether horizontal wells increase production compared with vertical wells. It lies in whether horizontal wells offer higher economic benefits than vertical wells. Therefore, under the guiding principle of enhancing the efficiency of horizontal wells (highly deviated wells), a parameter optimization method for horizontal wells (highly deviated wells) is constructed, with maximizing benefits as the optimization objective, and selecting the horizontal segment length (deviation angle) corresponding to the maximum net income of the horizontal well (highly deviated well) as the optimization result (Figure 3).

The oilfield company uses a 10-year investment payback period as its evaluation criterion for the following reasons.

(1) Fund efficiency and risk management

Fund efficiency: The payback period is a key metric for assessing investment efficiency. A shorter payback period accelerates capital recovery and improves fund utilization and liquidity, supporting additional investments and responding to unforeseen events.

Risk management: Oil and gas projects involve significant capital, and face risks such as geological uncertainties, market volatility, and policy changes. Setting an appropriate payback period helps to mitigate risks by ensuring timely investment recovery and minimizing potential losses from market or geological issues.

(2) Economic benefit assessment

Profit expectations: Oil and gas companies expect to achieve profitability within a set timeframe. Using a 10-year payback period as a benchmark helps to assess the long-term economic benefits.

Cost–benefit analysis: Comparing cumulative returns within the payback period with total investment costs allows the company to evaluate project feasibility.

(3) Planning and management

Long-term planning: A 10-year payback period provides a long-term framework for planning and strategic alignment with company goals.Project Management: Setting a clear payback period ensures that the project management team focuses on progress and cost control, meeting timelines and achieving timely investment recovery.

(4) Industry practices and standards

Industry Practices: In the oil and gas sector, a 10-year payback period is widely accepted as a reasonable evaluation standard, reflecting industry expectations.

Comparison Standards: This period facilitates comparisons with other projects or companies, aiding in the evaluation of relative performance.

The output value of oil and gas wells is dictated by their cumulative production. Based on empirical values, a 10-year investment recovery period is established as the evaluation period. The world natural gas futures price in 2024 is chosen as $\$3.0/\text{m}^3$. The production allocation for oil and gas wells is based on a quarter of the open-flow capacity. The annual effective production time is set at 340 days, and the commodity rate of natural gas and oil is fixed at 95% (85% for high-sulfur gas reservoirs). Consequently, the output value formed by the gas well within the evaluation period can be expressed as follows:

$$P_V = 0.95 \times 3.0 \times 10 \times 340 \times q_{AOF}/4 = 4560\, q_{AOF} \quad (1)$$

The output value generated by high-sulfur gas wells during the evaluation period is expressed as follows:

$$P_V = 0.85 \times 3.0 \times 10 \times 340 \times q_{AOF}/4 = 3955\, q_{AOF} \quad (2)$$

The development cost of a gas well encompasses both drilling costs and natural gas production operating expenses incurred during the evaluation period. Drilling costs mainly comprise equipment costs, drilling fees, tripping fees, cementing fees, completion fees, and technical service fees. Among these, equipment costs, drilling fees, tripping fees, and technical service fees are all functions of the drilling time. The longer the drilling time is, the higher the total cost becomes. Assuming an average natural gas production operating expense of 1.0 US dollars per cubic meter in China in 2024, the development cost of the gas well during the evaluation period can be presented as follows.

$$C = C_{drill} + 10 \times 340 \times 1.0 \times q_{AOF}/4 = C_{drill} + 850\, q_{AOF} \quad (3)$$

The net income obtained by a gas well during the evaluation period is calculated by subtracting its development cost from the output value generated during the evaluation period, as follows:

$$\mathrm{N_P = P_V - C = 3710\, q_{AOF} - C_{drill}} \quad (4)$$

The net income obtained from high-sulfur gas wells during the evaluation period is calculated as follows:

$$N_P = P_V - C = 3105\, q_{AOF} - C_{drill} \quad (5)$$

In Equations (4) and (5), both q_{AOF} and C_{drill} are functions of the horizontal segment length (well deviation angle). Therefore, the size of the N_P value is ultimately directly related to the horizontal segment length (well deviation angle). When the N_P value reaches its maximum, the corresponding horizontal segment length (well deviation angle) is the reasonable horizontal segment length (well deviation angle) for a horizontal well (high-deviation well). It should be noted that due to the involvement of many empirical parameter values in Equations (1)–(3), the size of these parameters is closely related to the development of the market economy and drilling and completion technology. Therefore, Equations (4) and (5) for calculating net income are not fixed calculation formulas. They are listed here merely to demonstrate a feasible unique method for optimizing the horizontal segment length (well deviation angle).

3.2.2. Scenario 2: HRV ≤ 1

When horizontal wells cannot increase the open-flow capacity of gas wells to achieve production increase, the choice of well type for gas reservoir development can only be made between highly deviated wells and vertical wells, and optimization of the inclination angle of highly deviated wells is required.

3.3. Analysis of Controlled Reserve Constraints for Horizontal Wells (Highly Deviated Wells)

The determination of the production value of horizontal wells (highly deviated wells) already implies the assumption that "horizontal wells (highly deviated wells) possess geological reserves that are commensurate with their stable production". This demands that horizontal wells (highly deviated wells) have adequate reserve bases, that is, the controlled reserves of horizontal wells corresponding to the optimal horizontal section length, or the controlled reserves of highly deviated wells corresponding to the optimal well deviation angle, should be greater than their respective economic limit recoverable reserves. The controlled reserves are determined using the volumetric method.

$$G_g = 10^{-8}\pi {r_e}^2 h\Phi S_g / B_g \quad (6)$$

G_g—controlled reserves of the gas well, 10^8 m^3. r_e—gas supply radius of the gas well, m. h—effective reservoir thickness, m. Φ—effective porosity, %. S_g— gas saturation, %. B_g—natural gas volume factor.

Economic limit recoverable reserves are the lower limit of reserves for achieving beneficial extraction from gas wells. In essence, they refer to the cumulative gas production when the output value of the gas well equals its development cost.

Conventional gas reservoir:

$$G_{EL} = \mathrm{C}/(0.892 \times 0.95) = 1.18\ \mathrm{C} \quad (7)$$

High sulfur gas reservoir:

$$G_{EL} = \mathrm{C}/(0.892 \times 0.85) = 1.32\ \mathrm{C} \quad (8)$$

G_{EL}—the economic limit recoverable reserves of the gas well, 10^8 m^3. C—the development cost of the gas well, 10^4 dollars.

If the controlled reserves of a horizontal well (highly deviated well) are less than its economically recoverable reserves, this means that the reservoir conditions of the horizontal well (highly deviated well) cannot meet the reserve requirements determined by the development costs. Therefore, it is not advisable to use horizontal wells (highly deviated wells) for gas reservoir development.

The volumetric method is a commonly used approach in oil reservoir reserve calculations, but it also has some limitations. Its main drawbacks include measurement errors, changes in reservoir shape and size due to geological conditions, and storage pressure and temperature variations, as well as the impact of liquid level measurement errors and density changes on the results. Therefore, when applying the volumetric method for oil reservoir reserve calculation, these factors should be fully considered and corresponding measures taken to improve calculation accuracy.

To address the shortcomings of the volumetric method in oil reservoir reserve calculations, the following measures can be taken.

(1) Use more precise measurement tools and techniques to reduce errors in the measurement of reservoir size and shape. (2) Monitor the geological conditions and storage pressure and temperature changes of the reservoir, and adjust the reserve calculation parameters in a timely manner. (3) Utilize geological modeling and numerical simulation techniques to predict future changes in reservoir shape and size, thereby improving the accuracy of reserve estimation. (4) Employ high-precision liquid level gauges and ensure their correct installation to minimize liquid level measurement errors. (5) Fully consider the influence of crude oil density on factors such as composition, temperature, and pressure during reserve calculation.

In addition, by combining other reserve calculation methods, such as the material balance method, the pressure decline method, and the production decline curve method for mutual verification and calibration, and by comparing the calculation results of the different methods, possible errors can be identified and corrected, thereby enhancing the accuracy of reserve calculation.

3.4. Comparison and Selection Between Horizontal Wells and Vertical Wells (Highly Deviated Wells and Vertical Wells)

By the conclusion of step three, a provisional choice will have been made between horizontal wells and highly deviated wells. Nevertheless, this choice is not conclusive. Subsequently, a more elaborate and profound comparison needs to be carried out between horizontal wells and vertical wells, or between highly deviated wells and vertical wells. During this process, we remain steadfastly adherent to the efficiency criteria for well type optimization, and employ net income comprehensively and stringently to conduct precise comparisons. The well type corresponding to the higher net income will be determined as the ideal well type for gas reservoir development, providing distinct and effective guidance for subsequent gas reservoir development work.

4. Application

(1) Oil and gas reservoirs unsuitable for horizontal wells

For ultra-low-permeability reservoirs (permeability below 0.1 mD; it should be emphasized that this threshold is not constant, but increases with a decrease in formation pressure, a decrease in reservoir thickness, or an increase in anisotropy), especially those with significant thin-layer characteristics, despite the consideration of relevant data and actual conditions, horizontal wells show significant effectiveness in increasing production compared to vertical wells. However, due to the relatively small production scale of horizontal wells, the corresponding output value is also at a lower level, and its net income may not only be negative, but in some unique cases, it may even be within a very low numerical range. It is obvious that this result of only increasing production and not improving efficiency is significantly inconsistent with the criteria followed by well type optimization. Therefore, considering various factors and actual situations, overall, it is not suitable to carry out development work through horizontal wells for low-permeability thin reservoirs from the perspectives of development benefits and actual effectiveness.

(2) Oil and gas reservoirs unsuitable for highly deviated wells

Thin reservoirs are generally not suitable for exploitation using highly deviated wells [43]. Firstly, in low-permeability thin reservoirs, the production capacity of highly deviated wells is relatively small, and the generated output value is also at a low level. In this case, it is often difficult to achieve the goal of efficient exploitation. This is because the geological conditions of low-permeability thin reservoirs themselves have certain limitations, and coupled with the characteristics of highly deviated wells, their exploitation effect is greatly limited. Secondly, in high-permeability thin reservoirs, the exploitation benefits of highly deviated wells are usually lower than those of horizontal wells. This is mainly due to the more obvious advantages of horizontal wells in high-permeability thin reservoirs, which can more effectively improve exploitation efficiency and production, thereby creating higher economic benefits.

Highly deviated wells face challenges in terms of fluid transport, causing extraction difficulties. If such wells are to be developed under high-water-cut conditions, thorough and detailed evaluations should be conducted. Multiple factors, including but not limited to geological conditions, extraction costs, expected returns, technical feasibility, etc., need to be comprehensively considered to ensure the scientific and rationality of the development plan.

(3) Oil and gas reservoirs suitable for highly deviated wells

In the context of extraction from high-permeability thick reservoirs, highly deviated wells typically yield higher extraction benefits compared to horizontal and vertical wells. This is primarily attributed to the geological conditions of high-permeability thick reservoirs, which provide favorable support for the utilization of highly deviated wells. The unique wellbore structure and drilling method of highly deviated wells enable them to more comprehensively contact the reservoir, thereby enhancing the extraction efficiency and output of oil and gas. In comparison, the extraction effectiveness and benefits of horizontal and vertical wells may be relatively inferior under such geological conditions.

(4) Oil and gas reservoirs suitable for horizontal wells

In the extraction operations of high-permeability thin reservoirs, horizontal wells typically yield higher extraction benefits than highly deviated wells and vertical wells. This is due to the geological characteristics and fluid flow characteristics of high-permeability thin reservoirs, which create suitable conditions for the full utilization of the advantages of horizontal wells. The longer horizontal section of horizontal wells can traverse the reservoir to a greater extent, increasing the contact area with the reservoir, thereby enabling more efficient extraction of oil and gas resources. In contrast, highly deviated wells and vertical wells, due to the limitations of their wellbore structures and drilling methods, have a relatively smaller contact area with the reservoir in such geological conditions, resulting in relatively lower efficiency and final production of oil and gas extraction, thus making the extraction benefits inferior to those of horizontal wells.

(5) Oil and gas reservoirs suitable for vertical well modification

Previous analysis has shown that, for low-permeability thick reservoirs, unmodified horizontal wells do not offer a significant production increase advantages over unmodified vertical wells. Moreover, it can be clearly observed from actual production data and related research that the productivity of unmodified horizontal wells is far inferior to that of modified vertical wells (the production increase ratio is less than 1), and this characteristic is extremely prominent. The reason for this situation is due to the geological characteristics of low-permeability thick reservoirs themselves, as well as the differences in wellbore structure, production methods, etc. between unmodified horizontal wells and modified vertical wells. Therefore, for such reservoirs with unique geological conditions and production characteristics, in order to effectively increase the production of gas wells, it is appropriate to implement measures such as large-scale fracturing or acidification of vertical wells, in order to optimize the production effect and achieve higher oil and gas output.

When evaluating in strict accordance with the aforementioned well type optimization process, if there are no substantial differences in technical indicators among different well types, it is essential to take into account other technical management and policy-related factors to make an informed decision. For example, for gas reservoirs with extremely complex geological conditions, or where the level of geological understanding is still relatively low, to minimize potential risks during the drilling process, and based on mature and proven technological applications, it is advisable to give priority to the use of vertical wells for extraction. To significantly accelerate the overall cycle of capacity construction, it is appropriate to utilize vertical wells with a relatively short drilling cycle for extraction, which can effectively shorten the construction time and enhance efficiency. To better facilitate the smooth implementation of on-site technological breakthrough experiments for processing gas wells, and thereby obtain more valuable data and experience, horizontal wells or highly deviated wells should be chosen for extraction (Table 1).

Table 1. Well type adaptability evaluation of reservoirs with different characteristics.

Suitable Well Type	Reservoir Characteristics
Reconstructed straight well	Ultra-low permeability and thick layer
High-inclination well	Low-permeability thick layer
Horizontal well	Low-permeability thin layer

5. Conclusions

When the steady-state production ratio (HRV) is less than 1, a vertical well is more appropriate for gas wells. Conversely, when the HRV is greater than or equal to 1, horizontal and highly deviated wells exhibit significant advantages over vertical wells. Considering factors such as gas well output, costs, and net profit, an optimal horizontal section length of 800 m yields the best results. For ultra-low-permeability thick reservoirs, vertical wells are preferred; for low-permeability thick reservoirs, highly deviated wells are suitable; and for low-permeability thin reservoirs, horizontal wells are recommended.

By employing advanced technologies to assess the suitability of horizontal wells and predict their stimulation effects, and through a comprehensive evaluation of various factors, the analysis results demonstrate that the adaptability of horizontal well development aligns with the production dynamics characteristics of different gas reservoirs. This provides a robust foundation for evaluating the suitability of horizontal wells and determining the optimal development strategy for gas reservoirs.

Due to evolving factors, such as ongoing innovations in drilling and completion technologies, gradual improvements in reservoir modification techniques, and market-driven fluctuations in natural gas prices, the evaluation of horizontal well development benefits will vary over time. These dynamic factors interact, leading to changes in evaluation results across different periods. These alterations may be reflected in the evaluation values of development benefits, or they may be reflected in the necessity of adjustments to development strategies.

In the development of oil and gas reservoirs, permeability, porosity, fluid properties, wellbore roughness, wellbore radius, and reservoir fluid viscosity, among other parameters, are subject to dynamic changes, such as pressure decline and phase changes. Therefore, a non-stationary production capacity prediction method that takes into account the dynamic changes of the reservoir and the wellbore flow characteristics is needed to accurately predict the production capacity of an oil or gas well under different timeframes and conditions.

Author Contributions: H.Z. and J.C.: writing—original draft, writing—review and editing, project administration, conceptualization. X.Z. and L.M.: conceptualization, funding acquisition, project administration. Y.M.: resources, data curation, formal analysis, methodology. H.J. and B.Y.: visualiza-

tion, validation, methodology, investigation, formal analysis, data curation. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Digital Technology Company of PetroChina Xinjiang Oilfield Company, grant number 2024XJZD1003.

Data Availability Statement: All data, models, or code generated or used during the study are available from the corresponding author on request.

Acknowledgments: Thank you to the company's project team for their support of this manuscript.

Conflicts of Interest: Authors Haitao Zhang, Jianpeng Cheng, Xin Zhang, Yu Miao, Huining Jiang and Bo Yu were employed by the company PetroChina Xinjiang Oilfield Company. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest. The funder was not involved in the study design, collection, analysis, interpretation of data, writing of this article, or decision to submit it for publication.

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