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Application of Waterflood Characteristic Curves in the Estimation of Recoverable Reserves in the S Block of the Yanchang Oilfield

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ABSTRACT

Waterflood characteristic curves are essential tools for estimating recoverable reserves in oilfields, accurately representing the dynamics of waterflood development and providing reliable support for reserve evaluations. They offer significant guidance for optimizing development plans and improving resource utilization efficiency. This study focuses on the S block of the Yanchang Oilfield, utilizing production dynamic data from 128 wells. The research systematically applies Type A waterflood characteristic curves and calibrated Type A waterflood characteristic curves to estimate recoverable reserves and predict waterflood recovery factors. The results show that the dynamic geological reserves calculated using the Type A waterflood curve amount to 714.29×10^4 t, with technical recoverable reserves of 260.49×10^4 t and a recovery factor of 36.47%. The calibrated Type A waterflood curve (calibration coefficient C=17.10) yields dynamic geological reserves of 1875×10^4 t, technical recoverable reserves of 613.21×10^4 t, and a recovery factor of 32.70%. A comparison indicates significant differences in the results of the two methods, primarily due to the calibration curve's adjustment for non-ideal waterflood conditions, such as reservoir heterogeneity and early development data deviations. This study not only enriches the application of waterflood characteristic curves in oilfield development but also provides data support for dynamic evaluation and subsequent optimization of development plans for the S block of the Yanchang Oilfield. It offers valuable insights for the estimation of recoverable reserves in similar waterflood reservoirs.

KEYWORDS

Yanchang Oilfield S Block; Waterflood Characteristic Curves; Technical Recoverable Reserves Estimation; Recovery Factor Prediction.

1. INTRODUCTION

Waterflood characteristic curves are an important method in reservoir engineering for evaluating the effectiveness of waterflood development and predicting recoverable reserves. By establishing a quantitative relationship between cumulative oil production and cumulative water production, these curves provide essential technical support for dynamic analysis of oilfield development[1-2]. Since the introduction of the Type A waterflood characteristic curve, it has been widely applied in waterflood oilfield development both domestically and internationally due to its suitability for medium viscosity reservoirs and ease of calculation[3-5]. However, actual reservoir development is influenced by factors such as geological complexity (formation heterogeneity, pore structure differences), fluid properties (crude oil viscosity, formation water salinity), and development methods (well pattern density, water injection intensity). As a result, traditional waterflood characteristic curves often suffer from poor linear fitting accuracy due to early data dispersion or non-ideal waterflood conditions (edge and bottom water interference, localized water breakthrough), which affects the reliability of reserve predictions. Therefore, calibration methods are necessary to optimize the fitting accuracy.

Type A waterflood curves are applicable to waterflood development and waterflood reservoirs with active water bodies. They are primarily used in the analysis and prediction during the oilfield development stage, especially for evaluating the effectiveness of waterflood development, predicting production changes, and forecasting the rise in water cut. The application conditions mainly include the oilfield being in the waterflood development phase and the availability of complete and reliable cumulative oil production and cumulative water injection data. The key feature of the Type A curve is its linear section in a semi-logarithmic coordinate system, with cumulative oil production on the x-axis and cumulative water production on the y-axis. The slope and intercept of this straight line have specific geological significance and can reflect the effectiveness of waterflooding and the development approach. A smaller slope indicates a better development effect with a slower increase in water cut, while a larger slope suggests a poorer development effect. The straight line segment of the Type A waterflood curve is parallel, and the slope mainly depends on the geological reserves of the oilfield[6]. Using the Type A waterflood curve, key parameters such as remaining recoverable reserves, recovery factor, maximum water production, and ultimate recovery factor can be calculated, providing essential information for long-term planning and decision-making in oilfield development.

The S block of the Yanchang Oilfield is located in the middle and western part of the Yishan Slope in the Ordos Basin. Water injection development began in 2004, and a well-established water injection well pattern has been formed. However, the quantification and accurate calculation of recoverable reserves in this block remain lacking, and the existing evaluations fail to sufficiently integrate development dynamic data. This situation restricts the scientific design of subsequent development plans. Based on this, this paper takes the S block of the Yanchang Oilfield as the research subject, relying on the production dynamic data of the block. It systematically compares the application of Type A and calibrated Type A waterflood characteristic curves in recoverable reserve estimation, aiming to provide a reliable basis for dynamic evaluation and subsequent development strategy formulation for the block, while also offering reference for reserve evaluation and recovery factor prediction in similar waterflood reservoirs.

2. METHODS

2.1. Calculation of Dynamic Geological Reserves and Recovery Rate Prediction

When calculating dynamic geological reserves using waterflood curves, the Type A waterflood curve is the primary choice due to its clear physical meaning and simplicity in calculation. Tong (1978, 1981) indicated through extensive field practice and theoretical analysis that the slope (B value) of the linear segment of the Type A waterflood curve has a significant quantitative relationship with the dynamic geological reserves (N_{o}) of the reservoir. The expression for this relationship is as follows[7-8]:

$$N_{\mathrm{o}} = 7.5B' \tag{1}$$

In the equation, N_{o} represents the dynamic geological reserves in units of 10^4 t; $B' = 1/B$, where B is the slope of the Type A waterflood curve. This parameter is obtained through regression fitting of production data and reflects the dynamic rate of change between cumulative water production and cumulative oil production.

Based on the calculation results of dynamic geological reserves, the resource utilization efficiency of reservoir development can be further evaluated using the waterflood recovery rate formula, as follows[9]:

$$E_{\mathrm{R}} = \frac{\lg(WOR)_{\max} - [A + \lg(2.303 \times B)]}{N_{\mathrm{o}} \times B} \tag{2}$$

In the equation, E_R represents the waterflood recovery rate (%), which is the ratio of recoverable reserves under waterflood development conditions to dynamic geological reserves. It is a core indicator for evaluating the effectiveness of reservoir development. $(WOR)_{max}$ refers to the final economic limit water-to-oil ratio, which represents the volume ratio of water to oil produced when the oilfield reaches its economic extraction limit. In this calculation, the water-to-oil ratio corresponding to a water cut of 98%, the technical limit, is 49. A represents the intercept of the Type A waterflood curve, which is related to the initial development conditions of the reservoir.

This method links the linear characteristics of the waterflood curve with the geological parameters of the reservoir, enabling the quantitative calculation of dynamic geological reserves and waterflood recovery rate. It provides an important quantitative basis for evaluating reservoir development potential and formulating development strategies.

2.2. Type A Waterflood Characteristic Curve Prediction Equation

The traditional Type A waterflood characteristic curve is a classical model that describes the dynamic relationship between cumulative water production and cumulative oil production during the development of waterflood oilfields. Its expression is as follows[10-13]:

$$\lg W_{\mathrm{P}} = A + BN_{\mathrm{P}} \tag{3}$$

In the equation, W_p represents the cumulative water production, in 10^4 m^3, reflecting the total amount of water produced during the reservoir development process. A and B are the curve fitting coefficients, obtained through regression of production data. N_p is the cumulative oil production, in 10^4 t, representing the total amount of crude oil produced up to the present during reservoir development.

Based on the above fundamental equation and considering the intrinsic relationship between water cut, oil production, and water production, the following key relationships can be further derived:

a. N_p-f_w Relationship

Water cut is an important indicator for characterizing the development stage of a reservoir, and its relationship with cumulative oil production can be derived from the waterflood characteristic curve:

$$N_{\mathrm{P}} = \frac{1}{B}\left[\lg\frac{f_{\mathrm{w}}}{(1-f_{\mathrm{w}})\times 2.303\times B} - A\right] \tag{4}$$

In the equation, N_p represents the recoverable reserves under waterflooding, in 10^4 t; f_w is the overall water cut, in %. In field practice, a water cut of 98% is typically considered the technical limit for oilfield development (at this point, the crude oil content in the produced fluid is very low, and the economic viability of extraction significantly decreases). Therefore, when $f_w = 98\%$, the N_p calculated using equation (4) represents the recoverable reserves under waterflooding for the reservoir.

b. W_p-f_w Relationship

The variation of cumulative water production with water cut can be described by the following equation, which is used to predict the maximum water production when the reservoir development reaches the technical limit:

$$\frac{f_{\mathrm{w}}}{1-f_{\mathrm{w}}} = 2.303\times B\times W_{\mathrm{p}} \tag{5}$$

When the reservoir development reaches the technical limit ($f_w = 98\%$), by substituting this water cut value and the slope B of the Type A waterflood curve into equation (5), the maximum water production during the waterflood development phase, W_p (in 10^4 m^3), can be calculated.

2.3. Calibration of the Type A Waterflood Characteristic Curve Prediction Equation

Compared to the traditional Type A waterflood curve, the calibrated Type A waterflood characteristic curve optimizes the linear features of the curve by introducing a calibration coefficient C. Its expression is as follows[14]:

$$\lg(W_p + C) = A_1 + B_1 N_p \tag{6}$$

In the equation, A_1 and B_1 are the fitting coefficients of the calibrated curve (A_1 is the intercept, B_1 is the slope), obtained through regression of the calibrated data. C is the calibration coefficient, which physically represents a systematic correction of the cumulative water production to eliminate deviations caused by non-ideal waterflood factors, allowing the curve to more accurately present linear characteristics on a semi-logarithmic scale.

The key to the expression of the calibrated Type A waterflood characteristic curve is determining the calibration coefficient C. In this study, the method proposed by Chen (1982) was used for calculation. The specific steps are as follows[15]:

On the uncalibrated Type A waterflood curve, three characteristic points (N_{p1}, W_{p1}), (N_{p2}, W_{p2}), and (N_{p3}, W_{p3}) are arbitrarily selected, with the condition that the cumulative oil production of the middle point is the arithmetic average of the cumulative oil production of the two surrounding points, i.e.:

$$N_{p2} = \frac{1}{2}(N_{P1} + N_{P3}) \tag{7}$$

Based on the cumulative water production values W_{p1}, W_{p2}, and W_{p3} of the three characteristic points mentioned above, the calibration coefficient C can be calculated through mathematical derivation, as follows:

$$C = \frac{W_{P1}W_{P3} - W_{P2}^2}{W_{P1} + W_{P3} - 2W_{P2}} \tag{8}$$

3. RESULTS AND ANALYSIS

3.1. Dynamic Development Characteristics of the Study Area

The Ordos Basin is a major oil and gas basin in China, known for its strong structural stability and minimal tectonic activity during its geological evolution. The S block of the Yanchang Oilfield is located in the Wuqing area of the basin, structurally belonging to the middle-western part of the Yishan Slope, a first-level structural unit of the basin. As a highly valuable structural unit for oil and gas exploration and development, the Yishan Slope presents a gentle westward-dipping monocline structure. The regional tectonic pattern is simple, with bedding dip angles generally less than 1°[16]. This low-amplitude tilted structural characteristic provides relatively stable geological conditions for oil and gas migration and accumulation, laying the foundation for the effective establishment and balanced displacement of the injection-production system in the subsequent waterflood development of this block.

A total of 128 wells were selected for production dynamic data analysis (from January 2004 to November 2013). The production dynamic curves show (Figures 1 and 2) that the annual cumulative oil production exhibits a steady growth trend, with a cumulative oil production of 56.36×10^4 t. The role of the water injection well network is significant, providing reliable data for the analysis of the waterflood characteristic curve.

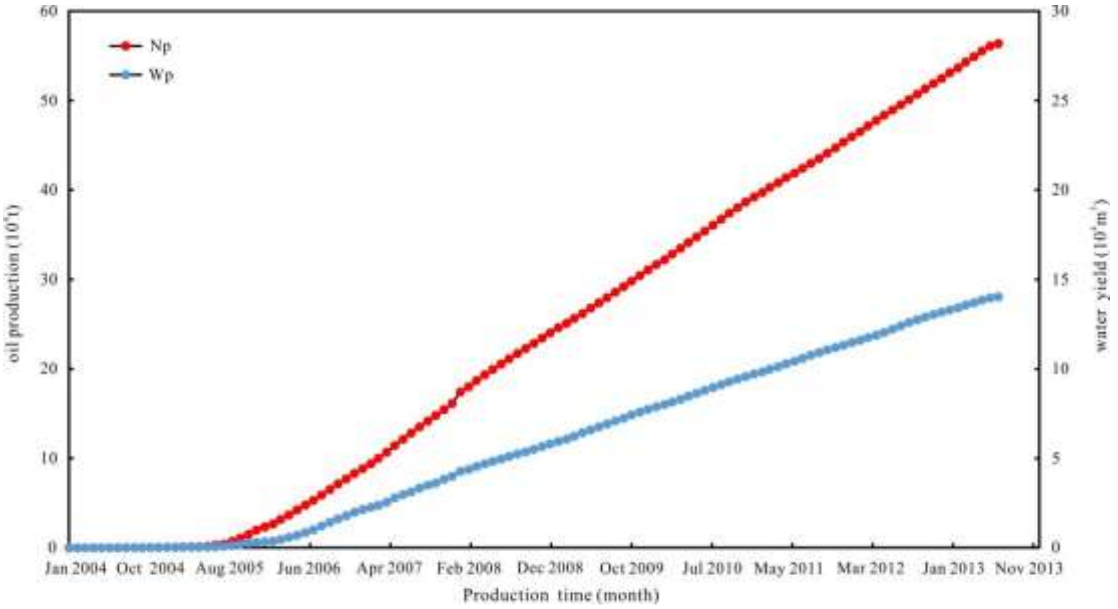

Figure 1. Production Dynamic Curves of the Well Area in S Block of Yanchang Oilfield

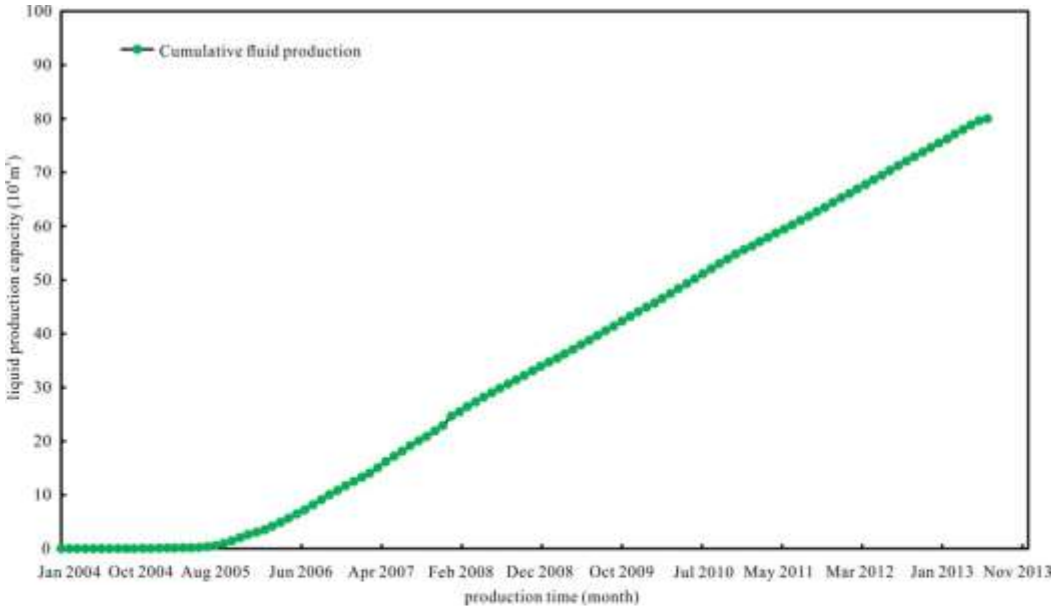

Figure 2. Cumulative Liquid Production Dynamic Curve of the Well Area in S Block of Yanchang Oilfield

3.2. Calibration Results of the Type A Waterflood Characteristic Curve

Based on the actual production data from the S Block of Yanchang Oilfield, a total of 128 wells were selected for calculation, and the Type A waterflood characteristic curve was plotted. Suitable linear segments were selected for regression fitting (the regression period was from September 2009 to July 2013). The intercept (A) and slope (B) of the linear segment of the Type A curve were obtained. Using a limit water cut of 98%, the corresponding recoverable reserves were calculated (Figure 3). Using equations (4) and (5), the technical recoverable reserves for this block were calculated to be 260.49×10^4 t, with a maximum water production of 2026.34×10^4 m^3.

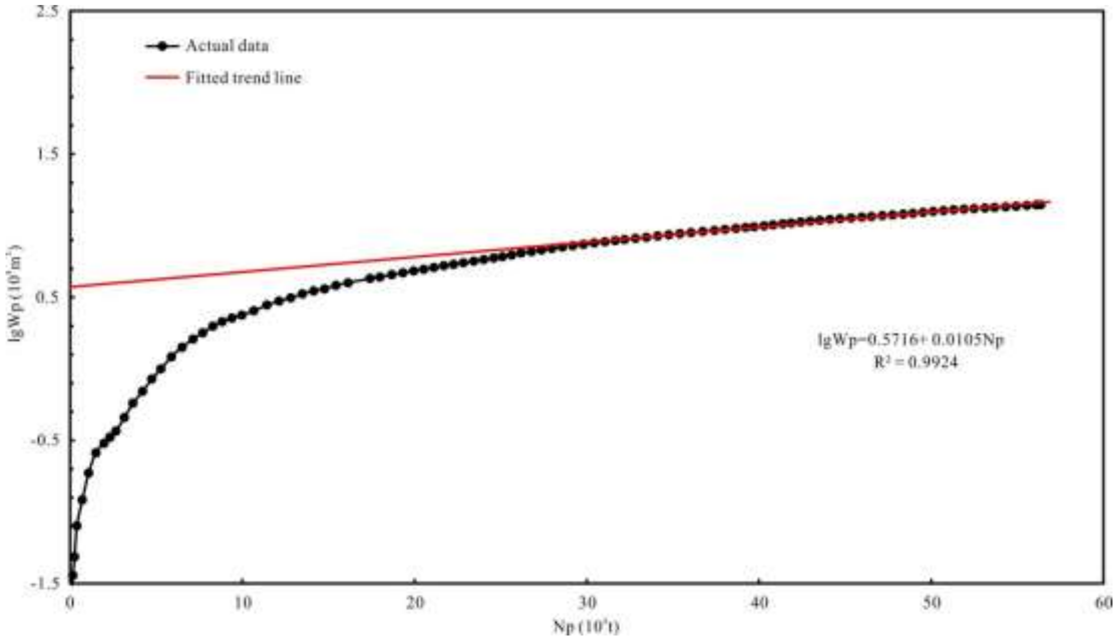

Figure 3. Type A Waterflood Characteristic Curve of S Block in Yanchang Oilfield

3.3. Calibration Results of the Type A Waterflood Characteristic Curve

The calibration coefficient C of the Type A waterflood characteristic curve, calculated using equations (7) and (8), is 17.1. The fitted regression equation for the trend line is $\lg(W_p + C) = 1.273 + 0.004N_p$ (Figure 4). Based on this calculation, the waterflood recoverable reserves are 613.21×10^4 t, with a maximum water production of 5319.15×10^4 m^3.

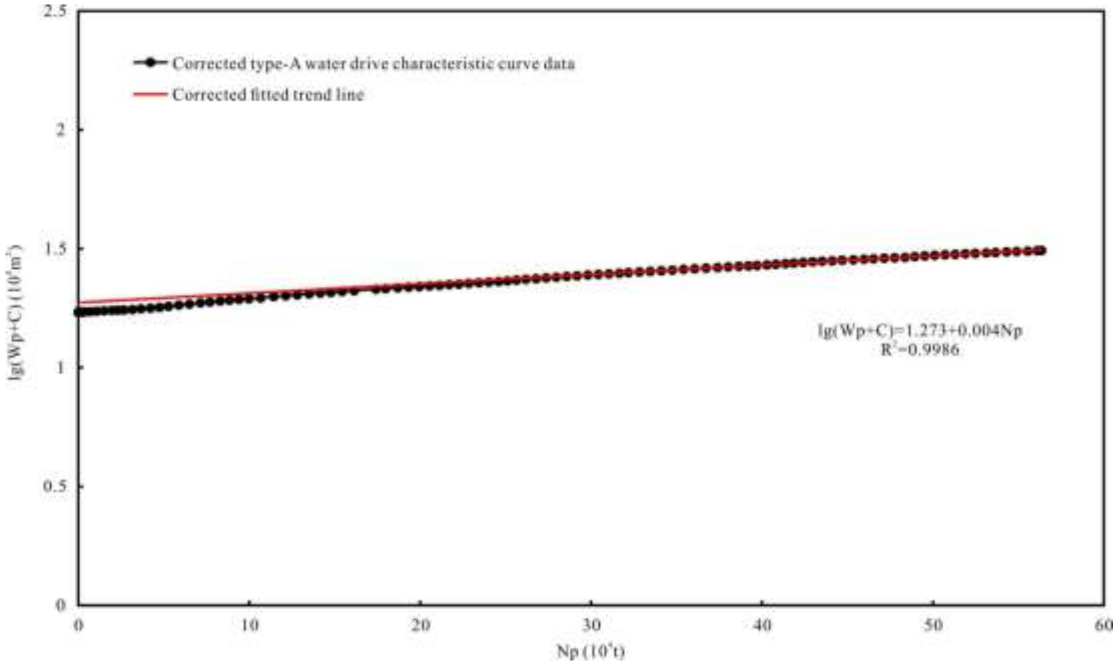

Figure 4. Calibrated Type A Waterflood Characteristic Curve of S Block in Yanchang Oilfield

3.4. Comparison of Results from Two Methods

The dynamic geological reserves calculated using the Type A waterflood curve are 714.29×104 t, while the dynamic geological reserves calculated using the calibrated Type A waterflood curve are 1875.00×104 t (Table 1). The recoverable reserves using the calibrated Type A waterflood curve (613.21×104 t) are significantly higher than those from the Type A curve (260.49×104 t). The difference mainly stems from the calibration coefficient C, which corrects the early non-linear segment data and improves the curve's adaptability to waterflood dynamics (R^2 increased from 0.9924 to 0.9986). In terms of recovery rate, the Type A curve shows a slightly higher recovery rate due to its smaller geological reserve calculation, but further validation is needed based on the actual geological conditions of the block.

Table 1. Waterflood Curve Characteristic Parameters of S Block in Yanchang Oilfield

Type	A	B	C	R^2	$N_o/10^4t$	E_R/%
Type A	0.5716	0.0105	/	0.9924	714.29	36.47
Calibrated Type A	1.2730	0.0040	17.10	0.9986	1875.00	32.70

4. CONCLUSION

1) The analysis of the waterflood characteristic curves for the S Block of Yanchang Oilfield indicates that both the Type A waterflood characteristic curve and the calibrated Type A waterflood characteristic curve can be effectively applied for recoverable reserves estimation in this block. Among them, the fitted correlation coefficient (R^2) of the calibrated Type A waterflood characteristic curve reaches 0.9986, higher than that of the Type A waterflood curve (R^2 = 0.9924), indicating better fitting accuracy and a more accurate reflection of the actual development dynamics of the block.

2) The quantitative calculation results show that the technical recoverable reserves obtained from the Type A waterflood curve are 260.49×10^4 t, with a corresponding waterflood recovery rate of 36.47%. The technical recoverable reserves calculated using the calibrated Type A waterflood curve are 613.21×10^4 t, with a waterflood recovery rate of 32.70%. The core difference in these results is attributed to the introduction of the calibration coefficient C in the calibrated Type A waterflood curve, which systematically corrects the cumulative water production, making the curve's linear characteristics more prominent and leading to differences in the calculated dynamic geological reserves and recovery rates.

3) To further improve the reliability of the recoverable reserves estimation for the S Block, it is recommended that future studies integrate reservoir numerical simulation techniques or other types of waterflood curves for validation. This will provide more accurate reserve parameters for the block's later development planning. In practical applications, it is essential to comprehensively consider the development stage of the oilfield, geological conditions, and the completeness of production data when selecting an appropriate waterflood model. This will enhance the prediction accuracy of technical recoverable reserves and recovery rates, guiding the design of water injection well network optimization and profile adjustment schemes, and providing a scientific basis for reservoir development decision-making.

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