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Application of Well-to-Surface Potential Monitoring Technology in Evaluating Profile Control Efficiency in Low-Permeability Reservoirs

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Abstract

Traditional evaluation methods for profile control in oilfields suffer from limitations such as the inability to achieve real-time monitoring, high costs, long evaluation cycles, and large discrepancies before and after treatment. As a novel dynamic monitoring approach, well-to-surface potential monitoring technology can capture potential variations that reflect fluid migration and distribution within the reservoir. This technique offers advantages including real-time monitoring, high accuracy, and high sensitivity. Based on the fundamental principles and forward modeling theory of well-to-surface potential monitoring, this study applies the method to the HuX-25 well group in the Hujianshan Oilfield to evaluate the effectiveness of profile control. Results show that potential monitoring reveals a significant expansion of the waterflooding swept area. Field data indicate that after the profile control treatment, the overall water cut decreased from 83.7% to 59.8%, while daily oil production increased from 8.36 t to a peak of 10.12 t, confirming notable effects of water reduction and oil enhancement. This technology provides a scientific basis for evaluating the effectiveness of profile control, optimizing oilfield development strategies, and improving recovery efficiency, demonstrating promising potential for practical applications.

Keywords

Potential method; dynamic monitoring; forward modeling; flooding adjustment evaluation.

1. Introduction

With the continuous growth of global energy consumption, oil and gas resources, as the dominant component of traditional energy, face unprecedented challenges in terms of efficient development and rational utilization. During oilfield development, water injection has long been recognized as a conventional technique to enhance oil recovery by effectively replenishing reservoir energy, maintaining formation pressure, and extending the production life of wells. However, due to the inherent heterogeneity of reservoirs, long-term water injection often results in preferential flow through high-permeability zones, leading to limited sweep efficiency, reduced displacement effectiveness, and the occurrence of issues such as water channeling and premature water breakthrough. In contrast, residual oil in low-permeability zones remains unswept and difficult to recover, resulting in significant resource wastage.

For instance, in the Changqing Oilfield, water injection development is frequently constrained by a narrow swept volume and severe injection-production imbalance. As a result, the overall recovery factor has remained below 20% for years, which severely restricts the economic benefits of field development. To address these challenges, reservoir adjustment techniques such as profile modification and profile control have been widely applied to improve injection conformance and expand the swept volume, thereby enhancing oil recovery. Nevertheless, because of the complex mechanisms and multiple influencing factors involved in profile control

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processes, real-time dynamic monitoring of treatment performance remains a critical challenge in formulating effective reservoir management strategies.

Conventional evaluation methods, such as production response analysis, water cut reduction assessment, water intake profile measurement, and tracer testing, all suffer from inherent drawbacks, including the inability to provide real-time monitoring, high operational costs, and long evaluation cycles[1]. In comparison, well-to-surface potential monitoring technology offers a unique advantage: by tracking potential variations associated with fluid movement, it provides a highly sensitive and precise means of characterizing dynamic changes in reservoirs. This technique has been successfully applied in various aspects such as residual oil distribution monitoring[2-5], evaluation of profile control performance[6-7], and fracture morphology characterization[8-9].In this study, the fundamental principles and forward modeling theory of well-to-surface potential monitoring are applied to the HuX-25 well group in the Hujianshan Oilfield. This method enables visualization of the dynamic interwell seepage field and unswept zones before and after profile control treatment, which, when combined with field production data, validates the effectiveness of the monitoring results. The study aims to provide an intuitive and practical approach to evaluating the performance of profile control treatments in low-permeability reservoirs.

2. Principle of Well-to-Surface Potential Monitoring Technology

The fundamental principle of the well-to-surface potential method is based on the conductivity differences between various fluids in the reservoir. Since fluids such as oil, water, and injected chemicals exhibit distinct electrical conductivities, their responses to an applied electric field differ significantly. By continuously monitoring potential variations at the wellhead, it becomes possible to infer the distribution and migration patterns of subsurface fluids.

The working principle of the well-to-surface potential method[10] is illustrated in Figure 1. A transmitter injects a constant current into the reservoir via supply electrodes A (typically located in the injection well) and B (placed in a nearby production well). Because the resistivity of the working fluid is lower than that of the surrounding rock, the injected current density is significantly higher in the fluid-bearing zone. The high degree of ionization of the injected fluid perturbs the natural electric field, resulting in measurable changes in surface potentials. These potentials are recorded by a receiver connected to measurement electrodes (M and N). After computational processing, the potential differences are converted into resistivity contour maps, revealing the subsurface oil–water distribution. By analyzing the direction and intensity of current flow, the method provides precise insights into the movement and redistribution of reservoir fluids, thereby supporting more effective development decisions.

A notable advantage of this technology is that it does not require direct physical contact with subsurface media. It offers high efficiency, precision, and real-time monitoring capabilities, making it a powerful tool for dynamic evaluation of reservoir processes.

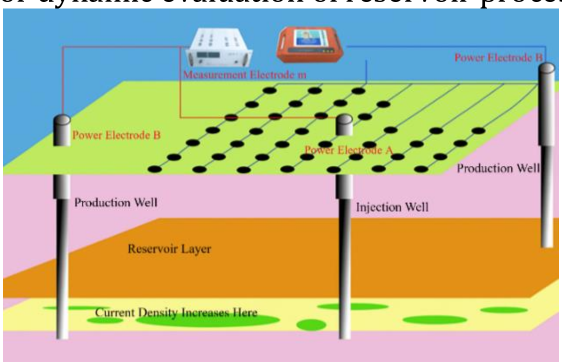

Fig. 1 Schematic Diagram of the Testing Principle

3. Theoretical Basis

3.1. Potential Distribution in Heterogeneous Media

For a three-dimensional heterogeneous reservoir, when a current source I is introduced at point A located on the surface boundary of the domain Ω, the potential ν in the medium satisfies Poisson's equation[11]:

$$\nabla\cdot(\sigma\nabla\nu)=-2I\delta(A),\in\Gamma s \quad (1)$$

where: σ is the electrical conductivity of the medium; ν is the potential at each grid node; ∇ν is the potential gradient, corresponding to the electric field intensity; I is the strength of the current source; δ(A) is the Dirac delta function that defines the location of the point current source.

3.2. Boundary Conditions

(1) Surface boundary (Γ_s)

The derivative of the potential along the normal direction n to the ground surface is zero, which can be expressed as:

$$\frac{\partial\nu}{\partial n}=0$$

This condition ensures that the potential at the boundary nodes is equal to that of their neighboring nodes within the control volume.

(2) Far-field boundary(Γ_∞)

According to the potential attenuation condition:

$$\frac{\partial\nu}{\partial n}+\frac{\cos(r,n)}{r}\nu=0$$

This reflects the fact that potential gradually diminishes with increasing distance from the current source.

3.3. Discretization.

The control volume method is employed to discretize Equation (1). The reservoir is divided into multiple grid cells, each representing a control volume. The center of each control volume is denoted as P, with adjacent nodes located in the north (N), south (S), east (E), west (W), top (T), and bottom (B) directions. The grid spacing is Δx, Δy, Δz, corresponding to the distances in the x, y, and z directions, respectively.

By applying Gauss's theorem, the divergence term is transformed into a flux across the surfaces of the control volume:

$$\int_V \nabla\cdot(\sigma\nabla\nu)dV=\sum_f\int_{Af}\sigma_f\nabla_\nu n_f dA \quad (2)$$

Where, σ_f is the electrical conductivity adjacent to the control volume surface A_f; ∇ν is the potential gradient, representing the electric field strength; n_f is the normal vector of face f, pointing outward from the control volume.

The potential gradient is approximated using the finite difference method. For control volume P, the potential differences between P and its neighboring nodes (E, W, N, S, T, B) represent the electric field gradients. These, combined with the conductivities and distances, yield flux approximations in each direction.

Thus, the discretized form of Poisson's equation for node P is written as:

$$a_P\nu_P=a_N\nu_N+a_S\nu_S+a_E\nu_E+a_W\nu_W+a_T\nu_T+a_B\nu_B+b \quad (3)$$

where: $a_N, a_S, a_E, a_W, a_T, a_B$ are the conductance coefficients between P and its neighboring nodes; $\nu_N, \nu_S, \nu_E, \nu_W, \nu_T, \nu_B$ are the potentials at adjacent nodes; $b=-2I\Delta V$ is the source term, which equals the injected current if the control volume contains a point source, otherwise, $b = 0$.

By assembling all nodal equations, the system can be expressed as a linear algebraic matrix equation:

$$Av = b \tag{4}$$

Where: A is the coefficient matrix containing conductance terms; v is the vector of unknown nodal potentials, and b is the source vector representing the contributions from current injection.

Solving the system provides the potential field distribution across the reservoir. The corresponding electric field can then be calculated by:

$$E = -\nabla v \tag{5}$$

This computed electric field distribution is subsequently used to analyze fluid migration and distribution patterns within the reservoir.

4. Field Application

4.1. Overview of the Test Area

The target formation of the Hujianshan Oilfield is the Yan-9 reservoir, located at a burial depth of 1515 m. The formation temperature is 54.82 °C, with an average effective thickness of 8.9 m, average porosity of 16.9%, and average permeability of 24.1×10^{-3} μm^2. The initial oil saturation is 50.3%. The reservoir is classified as a structural–lithologic reservoir with elastic dissolved gas drive, and bottom water is widely developed across the area. The original formation pressure was 11.4 MPa. The crude oil has a viscosity of 6.62 mPa·s and a density of 0.813 g/cm^3.

The HuX-25 well group was put into production in August 2009 from the Yan-9 layer. In March 2011, the well group was converted to water injection, corresponding to seven production wells with matching injection intervals. In June 2017, the injection intensity was increased, leading to a continuous rise in liquid production and a rapid increase in water cut. From October 2021 to May 2022, a viscoelastic self-regulating agent was applied, but water control results were unsatisfactory: the water cut increased from 64.0% to 65.2% during treatment, and after termination, the water cut rose rapidly. Given the relatively better performance of microgel + PEG-2C, another round of injection was carried out from September 2022 to January 2023. However, during this period, the water cut still increased from 67.6% to 71.2%, suggesting diminished effectiveness of repeated treatments.

In order to overcome the limitations of conventional profile control agents, a novel core–shell structured profile control agent was implemented for online deep profile control in the HuX-25 well group in August 2024. A “two-stage slug injection” strategy was adopted, targeting both near- and far-field dominant channels. In the first slug, a 3.0 wt% agent concentration was used to rapidly seal the main water-conducting channels. In the second slug, the concentration was reduced to 1.5 wt%, allowing for slower blocking of secondary flow paths and reinforcing the overall plugging effect.

Well-to-surface potential monitoring was employed to track the waterflooding behavior and swept volume within the injection intervals of the HuX-25 well group. This provided an accurate description of water injection distribution and offered a scientific basis for evaluating treatment effectiveness, adjusting injection strategies, and optimizing field development.

4.2. Implementation Scheme of Profile Control Monitoring

(1) Electrode Arrangement

The casing of HuX-25 well was used as supply electrode A. After surface cleaning and rust removal, it was connected via multi-strand copper cables to the A terminal of a high-power direct current transmitter. The return electrode B was installed approximately 1000 m away, either in a cased well or directly in the surface formation. Electrode B consisted of 10–50 solid iron rods (900 mm in length, 14 mm in diameter) driven vertically into the ground at 900 mm × 900 mm spacing. These rods were connected using bare copper wires to form an electrode array, which was then linked to the B terminal of the transmitter.

(2) Survey Line Layout

The casing of HuX-25 well served as the current source (electrode A), while the casing of a neighboring well 1500 m away acted as the return electrode (electrode B). Taking the wellhead as the origin of a local coordinate system, 18 radial survey lines were deployed at 20° intervals. Each line contained 12 potential measurement points (M electrodes) spaced at 50 m intervals, with a maximum observation radius of 600 m.

In accordance with the design of the well-to-surface potential survey, the field configuration was as follows: electrode A was connected to the wellhead, electrode N was positioned at the survey center, and electrode B was placed more than 1000 m away, grounded through either a cased well or a surface electrode array.

(3) Potential Measurements

The monitoring principle relies on the resistivity contrast between injected profile control agents, the surrounding rock, and formation fluids. The basic observation layout of the three-dimensional resistivity tomography method is illustrated in Figure 2. To minimize topographic interference, potential differences were measured by fixing the M electrode and progressively moving the N electrode outward along radial lines (N_1, N_2, N_3, ...). This concentric scanning approach enabled detection of potential variations at different orientations and distances. The resulting potential differences reflected dynamic changes in electrical properties within the treatment zone, thereby allowing real-time monitoring of agent migration pathways and treatment effectiveness.

All measured data were processed and interpreted in the laboratory, and the results were integrated with dynamic production information from the well group to evaluate the overall performance of the profile control treatment.

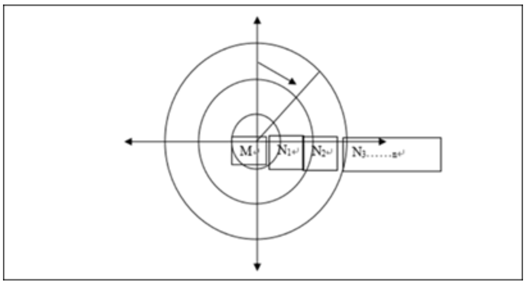

Fig. 2 Three-Dimensional electrical resistivity tomographic observation method

4.3. Analysis of Profile Control Effectiveness

4.3.1. Potential Monitoring Evaluation

Fig.3 and Fig.4 illustrate the potential distribution maps of the HuX-25 well group before and after the profile control treatment. The following observations can be made:

Before treatment: The potential map shows that the waterflood swept area was primarily distributed on the eastern side of the HuX-25 well group, elongated in an east–west orientation. This trend is consistent with the channel direction, suggesting the existence of a dominant water-conducting pathway.

After treatment: The waterflood swept area expanded significantly in the north–south direction, forming an irregular rhomboidal pattern. This indicates that the profile control treatment was effective.

Comparison before and after treatment: The previously dominant east–west channel (aligned with the paleo-channel) was effectively plugged, forcing injected water to divert laterally. As a result, the swept area expanded perpendicular to the channel orientation. Overall, the water front shifted southward. The high- and low-resistivity zones remained largely consistent across the two surveys, suggesting that the main water flow direction may still coincide with fracture development belts. This requires further verification through subsequent infill wells and optimization of development strategies.

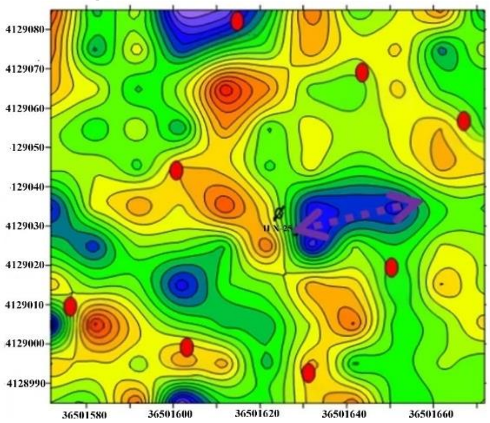

Fig. 3 Potential distribution map before profile control

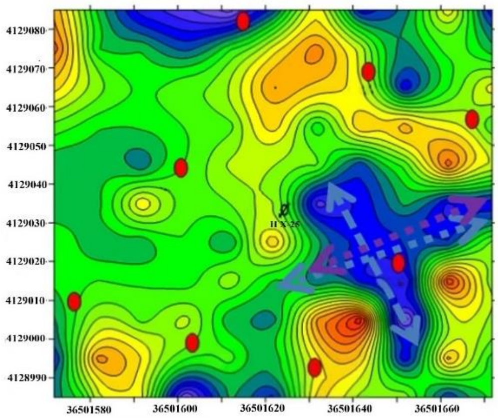

Fig.4 Potential distribution map after profile control

4.3.2. Evaluation of Water Cut Reduction and Oil Production Enhancement

As shown in Figure 5, before the profile control treatment, the HuX-25 well group maintained a relatively high water cut, while oil production exhibited a continuous declining trend. The daily liquid production remained relatively stable with only minor fluctuations.

After the treatment, the comprehensive water cut dropped rapidly, especially during the first several months of implementation, decreasing from 83.7% to 59.8%. This confirms the effectiveness of the water control process. Meanwhile, daily oil production increased significantly, rising from 8.36 t to a peak of 10.12 t. The results clearly demonstrate the positive impact of the treatment in reducing water production and enhancing oil recovery.

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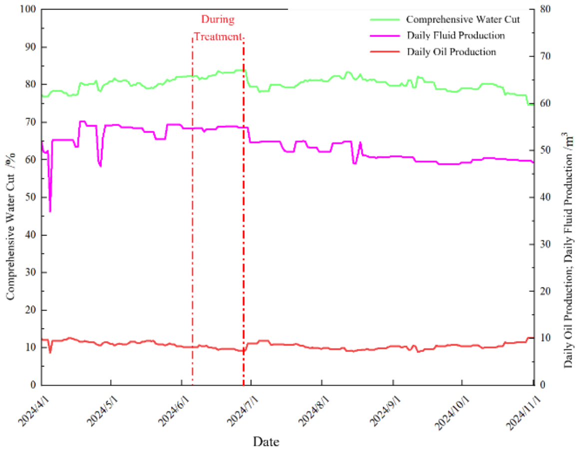

Fig. 5 Comparison of HuX-25 well group data before and after treatment

5. Summary

1. Based on the dynamic variation of the seepage field before and after profile control treatment, the well-to-surface potential monitoring method was proposed. By measuring potential variations at multiple surface points, imaging of the injection water sweep was achieved, enabling real-time monitoring of profile control processes.

2. A three-dimensional mathematical model of the well-to-surface potential method was established. Using the control volume approach, Poisson's equation for potential distribution in heterogeneous media was discretized with appropriate boundary conditions at the surface and far field. Through computational imaging, the underground seepage field was effectively visualized.

3. The method was applied to the HuX-25 well group in the Hujianshan Oilfield. Potential monitoring results showed that the swept volume of injected water expanded significantly after profile control. Combined with production performance data, the comprehensive water cut decreased from 83.7% to 59.8%, while daily oil production increased from 8.36 t to a peak of 10.12 t. These results confirm that the profile control agent successfully sealed dominant water channels and significantly improved post-treatment production performance.

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