Geological and technological substantiation of waterflooding systems in deposits with hard-to-recover reserves

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Abstract. The study of the process of developing oil reserves in one of the fields with hard-to-recover reserves of the Tournaisian stage of the Volga-Ural oil and gas basin. A significant increase in the oil recovery factor was established when using in-circuit waterflooding as compared to the development of deposits in natural mode. The influence on the degree of reserves recovery is shown by the density of the grid of wells, geological heterogeneity, the sweep efficiency by injection by thickness, variations in the injectivity profile in injection wells. Models are proposed to assess the parameters of the efficiency of waterflooding systems.

1. Introduction

A significant number of studies have been devoted to the issue of increasing the efficiency of the development of oil deposits using waterflooding [1–6]. Most of them concern highly productive facilities. However, significant oil reserves are concentrated in low-producing reservoirs, where water injection into the reservoir does not always give positive results, requires studying the waterflooding process and creating a scientific basis for making management decisions [7–14].

For oil deposits in the carbonate reservoirs of the Volga-Ural oil and gas province, there are usually a deterioration of reservoir properties, an increase in oil viscosity near the oil-water contact, an oxidized oil layer, sometimes - almost complete isolation of the reservoir from the reservoir water drive system. Due to the tendency for significant deterioration of reservoir properties of the water-oil zone, the systems of boundary waterflooding have not found wide application due to their low efficiency.

As the experience of reservoir development using contour waterflooding systems shows, the effectiveness of this measure is quite high, especially in the conditions of relatively highly productive deposits of the Kuibyshev, Orenburg and Perm regions. In the conditions of low-productivity objects, the efficiency is much lower, which is due to increased geological heterogeneity, low reservoir properties, high oil viscosity, lenticular distribution of reservoir rocks. Moreover, the influence of various geological parameters on the waterflooding efficiency is rather ambiguous in the conditions of various groups of objects, which imposes increased requirements on the choice of injection wells, their interposition relative to the producing wells, to the justification of injection pressure, etc. For example, in the conditions of the Tournaisian (Znamenskoye, Meleuzovskoye, Mancharovskoye, Sergeevskoye fields), Kashiro-Podolsky (Arzamskoye), Bashkir-Vereysky (Igrovskoye, Yugomashevskoye, Chetyrmanskoye) deposits of the platform part of Bashkiria in areas with insignificant effective oil-saturated strata (at pressures at the bottom of injection wells less than 0.7 of the rock pressure),
production wells are often not affected by injection, even when they are at a distance of 400–500 m from the injection well. Apparently, under these conditions, the distances between the production and injection wells should be less, as indicated by the experience of development of the Khorskhed field, where the effective oil-saturated thickness of 1.7 m did not become an obstacle to successful water injection into the reservoir.

At the same time, the experimental water injection into contour wells in the conditions of the thick Sakmaro-Artinsky limestones of the Ishimbay group of fields showed that the waterflooding efficiency was very low. This is due to the fact that, with significant layer-by-layer heterogeneity of reef massifs, water quickly breaks through several high-permeability interlayers into adjacent production wells and floods them. At the same time, a significant part of the section is not mined.

Zonal heterogeneity in reservoir properties also has a significant impact on the efficiency of contour waterflooding. The study of carbonate strata in drilled fields shows that secondary processes that improve the reservoir properties of a carbonate stratum proceeded unevenly not only along the section, but also in the area of individual structural and lithological rock differences. These processes are most developed at the highs and steep sides of structures and along the directions of tectonic fracturing.

Most of the low-producing oil deposits in the carbonate reservoirs of the Tournaisian stage of the platform part of Bashkiria are developed practically in natural modes. The final oil recovery factor (predicted) will not exceed 0.15–0.20.

At the same time, as the experience of developing the Tournaisian oil reservoir of the Znamenskoye field shows, the use of in-loop waterflooding with a ratio of injection and production wells of about 0.5 and lower injection pressures (on average - 4.2 MPa) will increase the oil recovery factor by almost 2 times.

2. Materials and methods

In this regard, the oil recovery process was studied in seven sections of this field, separated from each other by cutting rows of injection wells. Within each section, there was a focal flooding carried out; the density of the grid of wells varies from 13.8 to 30.2 ha/well (on average it is 22 ha/well) the ratio of injection (N_i) wells to production (N_p) – from 0.35 to 0.67 (on average – 0.5).

The field is characterized by the following geological and physical parameters: net pay thickness - 4.7 m; permeability coefficients - 0.019 μm², porosity - 0.12 fractional units, oil saturation - 0.8 fractional units; formation oil viscosity - 12.5 mPa ∙ s; gas content of reservoir oil - 29.3 m³ / t; saturation pressure - 6.1 MPa; initial reservoir pressure - 14.9 MPa; occurrence depth - 1600 m.

For each of the sections, calculated parameters reflected the geological heterogeneity, the final oil recovery factors under the condition of development in natural mode (η) and using the existing in-circuit waterflooding (η_wat). Furthermore, the increase in the oil recovery factor was determined due to the use of waterflooding (Δη).

Prediction of the value of h was carried out using a model obtained earlier from similar deposits in carbonate reservoirs, the development of which was carried out in a natural mode:

\[ η = 102 \left( K_{rr}^{0.5} \cdot K_{comp}^{0.5} \cdot H_t \right)/\left( μ_o^{0.5} \cdot S_g \right) - 108 \cdot H_t^{0.5} / \left( μ_o^{0.5} \cdot S_g^{0.5} \right) + 38.8 \cdot H_t^{0.5} / \left( μ_o^{0.5} \cdot S_g^{0.5} \right) - 31 / t_{melt} \]  

(1)

where \( K_{rr} \) – the proportion of reservoir rocks in the total thickness of the formation; \( K_{comp} \) – coefficient of compartmentalization; \( H_t \) – average thickness of oil-saturated layers, m; \( μ_o \) – viscosity of reservoir oil, mPa ∙ s; \( S_g \) – density of the grid of production and injection wells, ha / well; \( t_{melt} \) - initial formation temperature, K.

The \( η_wat \) value was predicted using the method of Kopytov A.V. on displacement characteristics. The gain was defined as the difference between \( η_wat \) and \( η \). The values of the calculated parameters are given in the table 1.
Table 1. Values of technological parameters for plots of the Znamenskoye field

| Parameter | Lot number |
|-----------|------------|
| Sg, ha/well | 1 2 3 4 5 6 7 |
| N_i/N_p | 30.2 14.8 14.0 36.6 13.8 20.8 22.2 |
| η_wat, % | 0.35 0.67 0.50 0.35 0.49 0.40 0.48 |
| η, % | 12.9 40.0 49.9 16.4 39.2 25.7 29.4 |
| Δη, % | 8.1 16.6 22.7 9.4 20.0 13.8 12.5 |

3. Results and discussion

It is clear that in areas with a denser grid of wells and more favorable geological characteristics hza can reach 50%, although in general for the field with N_i/N_p=0.5 and Sg=22 ha / well, the oil recovery factor will be 30.2%. At the same time, the average value will be only 14.7%.

The largest increase in oil recovery is observed in areas with a denser well pattern and better reservoir characteristics.

When constructing models and identifying the most informative geological and technological parameters (29 parameters were considered), which have a prevailing effect on the oil recovery process, the study uses stepwise regression analysis. Models of the following form were obtained:

\[ η_{wat} = 102 - 0.55W_{ot} - 1.12S_g + 7.13 K_{sw}/W_{ip}, \]
\[ Δη = 60.0 - 0.36W_{ot} - 0.68S_g + 2.75K_{sw}/W_{ip}, \]

where \( W_{ot} \) – variation in the thickness of oil-saturated layers, %; \( K_{sw}/W_{ip} \) is the ratio of the average value of the reservoir sweep efficiency by thickness to the variation of injectivity profiles (determined from the data of flow measurements in injection wells).

The values of the multiple correlation coefficients (R) are 0.95 and 0.94, respectively.

After excluding parameters reflecting geological heterogeneity, the following models were obtained:

\[ η_{wat} = 26.7 + 8.6K_{prod} - 1.22 S_g + 10.6 K_{sw}/W_{ip}, \]
\[ Δη = 26.6 - 5.68K_d + 5.84K_{prod} - 0.64 S_g + 3.38K_{sw}/W_{ip}, \]

Where \( K_{prod} \) – is the productivity factor, t / day · MPa; \( K_d \) – coefficient of dissection.

The R values are 0.87 and 0.89, respectively.

Models (2) and (3) can be used to predict the oil recovery factor and its growth in deposits similar to the investigated and drilled with a sufficiently dense grid of wells (so that \( W_{ot} \) can be calculated). At the same time, in the absence of flow measurement studies of injection wells, the values of \( K_{sw}/W_{ip} \) can be estimated using the obtained empirical formula:

\[ K_{sw}/W_{ip} = 2.63 + 0.049H_e + 0.73σ_{ot} + 0.31K_d, \]

where \( H_e \) is the average value of the effective oil-saturated thickness, m; \( σ_{ot} \) – root-mean-square deviation of oil-saturated layers thickness, m.

Models (4) and (5) can be used at the stage of field withdrawal from exploration, and the ratio \( K_{sw}/W_{ip} \) can be calculated by the formula:

\[ K_{sw}/W_{ip} = 1.81 + 0.22m - 0.47K_d, \]

where \( m \) is the average value of the porosity coefficient according to the geophysical survey data.

The R values of models (6) and (7) are 0.77 and 0.62, respectively.

4. Conclusion

The research makes the following main conclusions:

- the use of an intensive waterflooding system (close to areal) in the conditions of a low-productive Tournaisian reservoir of the Znamenskoye field will make it possible to increase the oil recovery factor by almost 2 times as compared to natural development;
- the density of the grid of production and injection wells, geological heterogeneity, the coefficient of coverage of the reservoir by injection in thickness and variation of the injectivity profile have a
significant impact on the oil recovery factor and its growth during the development of deposits using in-loop waterflooding:

- for the conditions of low-productivity deposits of the Tournaisian stage of the platform part of Bashkoria, the article proposes the models that allow predicting the effectiveness of the use of in-circuit waterflooding, as well as evaluating the coefficients of reservoir injection in thickness and variation of the injectivity profile using indirect geological and field data.

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