Calculation and forecast of current and final oil recovery from wells during depletion

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Abstract. The paper studies the impact of the productivity index and specific balance reserves attributable to a well, to current and final oil recovery during development of deposits under depletion conditions for different groups of deposits in carbonate reservoirs. It also proposes the dependencies, which allow controlling the change of current and final oil recovery in the process of development and evaluating the efficiency of the bottomhole zone treatment methods.

1. Introduction

When solving problems aimed at improving the efficiency of reservoir development, it is quite necessary to know not only the recoverable oil reserves, but also the degree and nature of the production of balance reserves by the area of deposits. This allows making correct and reasonable management decisions to regulate and improve development in order to increase current and final oil recovery [1-6].

2. Materials and methods

In the conditions of 14 low-production groups of carbonate reservoirs of the Urals-Volga oil and gas province [7], developed on a natural mode (at low reservoir properties, increased geological heterogeneity, lenticular shape of reservoir rocks, which is the reason for the absence and weak interaction between production wells), each of the wells was considered as a single object of operation, having its own specific balance reserves ($Q_{\text{m}}$) within the limits of conditionally defined drainage area:

$$Q_{\text{m}} = SH_{\text{m}}K_{\text{m}}\rho_{\text{m}}\theta,$$

where $S$ – oil productive acreage of conditionally defined drainage zone, $m^2$; $H_{\text{m}}$ – weighted average value of the net oil thickness within the conditionally defined drainage area, $m$; $m$ – porosity factor of the net oil thickness of reservoir rocks in a well; $K_{\text{m}}$ – oil saturation factor; $\rho_{\text{m}}$ – oil density in surface conditions, $kg/m^3$; $\theta$ – correction factor that takes into account oil shrinkage.

At the same time, conditionally defined drainage area of each well was determined by a boundary passing at an equal distance from two adjacent wells. The net oil thickness was determined by the isopach map from the ratio
\[ H_3 = \frac{H_{31}f_1 + H_{32}f_2 + \ldots + H_{3n}f_n}{f_1 + f_2 + \ldots + f_n}, \tag{2} \]

where \( H_{31}, H_{32}, \ldots, H_{3n} \) – average isopachs of the corresponding sections; \( f_1, f_2, \ldots, f_n \) – areas of certain reservoir compartments limited by neighboring isopachs within the conditionally defined drainage area.

Recoverable reserves for each well were determined using the depletion characteristics, and final oil recovery (\( \eta \)) – by formula

\[ \eta = \frac{Q_{new}}{Q_{old}}. \tag{3} \]

3. Results and Discussion

The productivity coefficient determined according to the data of hydrodynamic studies of wells takes into account all major parameters of productive formations and their saturating fluids in integral form: net oil thickness, permeability, sand-to-shale ratio, discontinuity, net-to-gross ratio, pore structure, oil viscosity, and is the most informative parameter determining the reservoir recovery rate [8-10]. Therefore, the influence of this parameter on oil recovery separately by wells of different groups of objects was studied.

Figure 1 shows the dependence of the final oil recovery factor on the productivity indices. As seen, under the conditions of each group of objects there is a natural increase in the production of oil reserves with an increase in productivity. This relationship is best described by linear functions (Table 1). For comparison, a similar dependence is given for the wells of the Tournaisian tier of the Shchelkanovsky field, which is highly productive, characterized by an active bottom water pressure, and the development indicators of which are comparable to those of terrigenous deposits.

Enhanced oil recovery with the productivity increase in each group is different, which is caused by several reasons. First, the features of the geological structure (which are not taken into account through the use of the productivity index) of formations; second, the different density of the production well pattern and the specific balance reserves per well; third, the activity of bottom and edge waters.

Within each group, the spread of points relative to the regression line is also explained by the different specific balance reserves per well, which have a significant effect on the final oil recovery.

Table 1 shows the regression equations and values of correlation coefficients, which vary from 0.386 to 0.857 and indicate a fairly significant relationship between final oil recovery and productivity, confirming that under conditions of low-production deposits in carbonate reservoirs, the productivity index is also an informative parameter, which largely determines oil recovery. However, as shown in Figure 1, the use of this parameter alone to predict oil recovery without taking into account other factors leads to significant errors that in some cases reach hundreds of percent.
Fig. 1. Impact of well productivity index on final oil recovery of conditionally defined drainage areas: (5) – dependence on wells of group 5 objects; (6) – dependence on wells of Shchelkanovskoye field.
Table 1. Regression equations of final oil recovery dependence on well productivity index

| Group of objects | Regression equation                                      | Correlation factor | Formula |
|------------------|---------------------------------------------------------|--------------------|---------|
| 1                | $\eta = 3.50 + 2.59 K_{qpol}$                           | 0.540              | 4       |
| 2                | $\eta = 4.31 + 4.53 K_{qpol}$                           | 0.816              | 5       |
| 3                | $\eta = 6.23 + 3.99 K_{qpol}$                           | 0.650              | 6       |
| 4                | $\eta = 5.09 + 2.14 K_{qpol}$                           | 0.501              | 7       |
| 5                | $\eta = 2.50 + 7.05 K_{qpol}$                           | 0.571              | 8       |
| 6                | $\eta = 2.16 + 3.15 K_{qpol}$                           | 0.579              | 9       |
| 7                | $\eta = 9.83 + 2.82 K_{qpol}$                           | 0.541              | 10      |
| 8                | $\eta = 2.50 + 6.00 K_{qpol}$                           | 0.568              | 11      |
| 9                | $\eta = 3.73 + 3.53 K_{qpol}$                           | 0.576              | 12      |
| 10               | $\eta = 1.53 + 4.72 K_{qpol}$                           | 0.770              | 13      |
| 11               | $\eta = 5.54 + 2.17 K_{qpol}$                           | 0.610              | 14      |
| 12               | $\eta = 4.15 + 1.90 K_{qpol}$                           | 0.386              | 15      |
| 13               | $\eta = 1.65 + 2.40 K_{qpol}$                           | 0.558              | 16      |
| 14               | $\eta = 1.98 + 2.69 K_{qpol}$                           | 0.685              | 17      |
| 15               | $\eta = 2.61 e^{0.39 h_{qpol}}$                         | 0.857              | 18      |

Since the analyzed deposits are characterized by lens-shape reservoir rocks, their low permeability, high geological heterogeneity [11], it seems natural to study the reserve recovery depending on specific balance reserves accounted for by the well.

Figure 2 shows that in the conditions of the considered low-production objects, there is a significant influence of the specific balance reserves on the final oil recovery over the entire range of changes $Q_{roi}$ from 50 to 800 thousand tons. Moreover, the nature and degree of oil recovery reduction with an increase in specific balance reserves are different in the conditions of each identified group of objects.

The conditionally defined drainage areas of the Tournaisian tier of Shchelkanovsky field are characterized by the highest oil recovery (27.5%) at $Q_{roi} = 100$ thousand tons, which is explained by high average productivity of the deposit (21.9 tons/day·MPa) with an active water injection mode of its operation. This is followed by Assel-Sacmaro-Artin objects of group 9 (at $Q_{roi} = 100$ thousand tons, $\eta = 25\%$). These deposits, having high net oil thickness, are opened by a dense pattern of production wells, as a result of which the number of unopened lenses and lenses not involved in the development is substantially less than in other groups of objects. The objects of the Tournaisian tier of group 1 are characterized by the lowest oil recovery (2.5%), which have the lowest productivity and density of producing wells among all groups of objects.
Fig 2. Impact of specific balance reserves on final oil recovery of conditionally defined drainage areas: 

- dependence on wells of group 5 objects; 
- dependence on wells of Shchelkanovo field.

On average, concerning the objects of the Tournaisian and Famennian tiers (groups 1-8), the increase of specific balance reserves from 100 to 200 thousand tons and from 200 to 400 thousand tons leads to the decrease of final oil recovery from 12.0 to 8.0% and from 8.0 to 5.0%, concerning the objects of Kashirskian, Podolskian, Vereiskian horizons and Bashkirian tier (groups 10-14) with a similar increase in specific reserves, the oil recovery will decrease from 14.8 to 9.0% and from 9.0 to 4.4%, and in general for all objects – from 14.0 to 9.1% and from 9.1 to 4.6%, respectively. The comparison of the decline rate of oil recovery with the increase of specific balance reserves per well by the objects of the Lower and Upper Devonian systems (groups 1-8) and the objects of the mid-
Carboniferous system (groups 10-14) shows (Fig. 2) that the impact $Q_{\text{wp}}$ on oil recovery within the groups of objects 10-14 is stronger due to their higher geological heterogeneity and worse reservoir properties.

The wide range of changes in the average value of final oil recovery by the group of objects with fixed values of specific balance reserves is largely caused by productivity. Thus, for example, at $Q_{\text{wp}} = 100$ thousand tons in descending order of magnitude, the objects of the Tournaisian and Famennian tiers are arranged as follows: $8 \rightarrow 5 \rightarrow 6 \rightarrow 7 \rightarrow 4 \rightarrow 2 \rightarrow 3$. Their average productivity is respectively: 6.05; 4.60; 2.35; 3.78; 2.87; 2.00; 1.82; 1.30 t/day·MPa. Among the objects of the mid-Carboniferous system, the order is as follows: $12 \rightarrow 10 \rightarrow 11 \rightarrow 14 \rightarrow 13$, with average productivity indices, respectively, 3.90; 3.61; 3.12; 2.35; 2.68 t/day·MPa. In other words, there is a clear trend of influence and productivity, which was also shown previously.

Despite the fact that in almost all groups (with the exception of group 5 and 15) the connections between $\eta$ and $Q_{\text{wp}}$ are significant (correlation coefficients vary from minus 0.383 to minus 0.742), a significant spread of actual points from the regression line is observed (Fig. 2). The analysis of the productivity of wells located in graphs above and below the regression line showed that on average for each group of objects, the productivity of wells above the regression line is more than the productivity of wells below the regression line by 2-5 times, i.e. the spread of points is also explained by non-accounting of well productivity. At the same time, the graphs are more qualitative and reflect only the downward trend in oil recovery with an increase in specific balance reserves and cannot be used separately to forecast oil recovery.

Under conditions of the analyzed objects the wells with higher productivity are usually confined to the zones with increased net oil thickness. With other equal values of parameters included in the calculation formula $Q_{\text{wp}}$ (except for $H_s$), the well with higher productivity should also have a large oil recovery within the conditionally defined drainage area. However, this well will also have large net oil thickness (compared to a well with lower productivity), and therefore large specific balance reserves, which simultaneously reduce oil recovery. In this case, this is caused by layer-by-layer heterogeneity.

In this regard, it is necessary to consider the joint impact of productivity and specific balance reserves on the final oil recovery of conditionally defined well drainage areas.

The search for the best dependence of the final oil recovery on the productivity index and specific balance reserves was carried out using fifteen functions of various types. The best dependency was determined by the largest value of the correlation coefficient. Figure 3 shows that when $K_{\text{wpco}}$ and $Q_{\text{wp}}$ used together, the relationship between these parameters and oil recovery has strongly increased. The correlation coefficient increased to 0.616-0.954. At the same time, the nature and extent of the impact of productivity and specific balance reserves on oil recovery changed slightly, but the constant decrease in the level of reserve production remained during the entire change interval $Q_{\text{wp}}$ for each of the fourteen groups of objects. In this regard, the dependencies shown in Figure 3 under number 15 are of particular interest. As can be seen, in the conditions of highly productive Tournaisian oil deposit of Shchelkanovsky oilfield (position A), the development of which is carried out under the natural active water mode, there is a limit of specific balance reserves equal to two hundred and fifty thousand tons, below which the oil recovery growth is significantly reduced. This decrease is caused by well interference due to overconsolidation of the production well pattern. In the conditions of low-production objects even with a tighter well pattern and smaller specific balance reserves, this value is absent. For comparison, the same graph shows the dependence of oil recovery on $Q_{\text{wp}}$ obtained by M.A. Tokarev for the conditions of the Bobrikov horizon of the Arlanskoye field containing terrigenous reservoirs. As seen, the nature of the oil recovery decline \ from specific balance reserves in the Tournaisian deposit of Shchelkanovsky field is similar to the deposits of the Arlanskoye field, and the lower values of oil recovery and marginal reserve per well are explained by lower productivity. The comparison shows that the difference in the nature and degree of production of oil reserves of highly productive carbonate and terrigenous deposits during their development at the mode.
of oil displacement by water and low-productive objects in carbonate reservoirs at the mode of energy depletion is quite significant, which indicates first of all the need to use denser patterns of production wells.

The comparison of the curves of final oil recovery dependence determined by the equations presented in this figure using the reference dependencies presented in [12] on specific balance reserves with average well productivity by the groups of objects indicates their good correspondence, which once again confirms the conclusion that there is no interaction between wells. This correspondence allows using the following formulas to calculate and forecast the current oil recovery $\eta_t$:

$$\eta_t^i = K_{npd} Q_{yo}^{-1} (701.7 - 224.3\ln t_i)$$

(19) (for groups of objects 1, 2);

$$\eta_t^i = K_{npd} Q_{yo}^{-1} (971.0 - 294.1\ln t_i)$$

(20) (for group of objects 3);

$$\eta_t^i = K_{npd} Q_{yo}^{-1} (843.0 - 265.6\ln t_i)$$

(21) (for group of objects 4);

$$\eta_t^i = K_{npd} Q_{yo}^{-1} (1032.7 - 317.8\ln t_i)$$

(22) (for group of objects 5);

$$\eta_t^i = K_{npd} Q_{yo}^{-1} (878.9 - 277.3\ln t_i)$$

(23) (for group of objects 6);

$$\eta_t^i = 882.0 K_{npd} Q_{yo}^{-1} e^{-0.238t_i}$$

(24) (for group of objects 7);

$$\eta_t^i = K_{npd} Q_{yo}^{-1} (977.3 - 337.2\ln t_i)$$

(25) (for group of objects 8);

$$\eta_t^i = K_{npd} Q_{yo}^{-1} (557.9 - 166.9\ln t_i)$$

(26) (for group of objects 9);

$$\eta_t^i = 1119.0 K_{npd} Q_{yo}^{-1} e^{-0.156t_i}$$

(27) (for group of objects 10);

$$\eta_t^i = K_{npd} Q_{yo}^{-1} (751.6 - 248.1\ln t_i)$$

(28) (for group of objects 11);

$$\eta_t^i = 524.0 K_{npd} Q_{yo}^{-1} e^{-0.139t_i}$$

(29) (for group of objects 12);

$$\eta_t^i = 441.0 K_{npd} Q_{yo}^{-1} e^{-0.116t_i}$$

(30) (for groups of objects 13, 14).
Fig. 3. Complex impact of $Q_{\text{res}}$ and $K_{\text{opd}}$ on oil recovery of conditionally defined drainage areas: \[\square\] – curve by reference dependence $Q_{\text{res}}=K_{\text{opd}}$; \[\square\] – curve by actual data; A, B – dependencies for Shchelkanovsky (Tournaisian) and Arlansky (Bobrik) deposits

The formulas to evaluate the final oil recovery will be as follows:

\[\eta = K_{\text{opd}} \sum_{i=1}^{\text{fin}} 701.7 - 224.3 \ln t_i\]  
(31)

(for groups of objects 1, 2):

\[\eta = K_{\text{opd}} \sum_{i=1}^{\text{fin}} 971.0 - 294.1 \ln t_i\]  
(32)
(for group of objects 3);
\[ \eta = K_{npd} Q_{\text{in}} \sum_{i=1}^{l_{\text{oil}}} 843.0 - 265.6 \ln t_i \] (33)

(for group of objects 4);
\[ \eta = K_{npd} Q_{\text{in}} \sum_{i=1}^{l_{\text{oil}}} 1032.7 - 317.8 \ln t_i \] (34)

(for group of objects 5);
\[ \eta = K_{npd} Q_{\text{in}} \sum_{i=1}^{l_{\text{oil}}} 878.9 - 277.3 \ln t_i \] (35)

(for group of objects 6);
\[ \eta = 882 K_{npd} Q_{\text{in}} \sum_{i=1}^{l_{\text{oil}}} e^{-0.238_i} \] (36)

(for group of objects 7);
\[ \eta = K_{npd} Q_{\text{in}} \sum_{i=1}^{l_{\text{oil}}} 977.3 - 337.2 \ln t_i \] (37)

(for group of objects 8);
\[ \eta = K_{npd} Q_{\text{in}} \sum_{i=1}^{l_{\text{oil}}} 557.9 - 166.9 \ln t_i \] (38)

(for group of objects 9);
\[ \eta = 1119 K_{npd} Q_{\text{in}} \sum_{i=1}^{l_{\text{oil}}} e^{-0.156_i} \] (39)

(for group of objects 10);
\[ \eta = K_{npd} Q_{\text{in}} \sum_{i=1}^{l_{\text{oil}}} 751.6 - 248.1 \ln t_i \] (40)

(for group of objects 11);
\[ \eta = 524 K_{npd} Q_{\text{in}} \sum_{i=1}^{l_{\text{oil}}} e^{-0.139_i} \] (41)

(for group of objects 12);
\[ \eta = 441 K_{npd} Q_{\text{in}} \sum_{i=1}^{l_{\text{oil}}} e^{-0.116_i} \] (42)

where \( l_{\text{oil}} \) – defined by formulas given in [12].

4. Conclusion
Formulas (19) – (42) allow solving the following development tasks:
- to forecast the current and final oil recovery during natural development knowing the initial productivity of certain deposits or their areas and different values of the average specific balance reserves;
- to control the change of current and possible final oil recovery during development;
- to evaluate the effectiveness of methods aimed at enhanced oil recovery.

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