Prediction of production well flow rates using survey data

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Abstract. The influence of geological and physical properties of the layers determined during geophysical studies on the maximum optimal flow rate of wells was studied for two groups of objects in terrigenous reservoirs of the Cretaceous age of Western Siberia. Multidimensional models were constructed. They allow for prediction of potential flow rates using indirect information when developing deposits in natural modes and using artificial waterflooding. An algorithm for substantiating selective and focal waterflooding, transfer of wells from other horizons and transfer of idle wells into the productive well stock was developed.

1. Introduction
One of the main activities in improving the efficiency of oil reservoir development is improvement of waterflooding systems and development of additional production wells [1–10]. When choosing foci for injection and operation of idle and transit wells, it is important to know the expected degree of interaction between injection and producing wells and the expected flow rates.

2. Methods and materials
These parameters are estimated on the basis of direct research according to hydrodynamic, tracer, flow-measuring studies and geological field analysis. At the same time, in the conditions of hundreds of fields located in vast areas, hundreds of thousands of production and injection wells, implementation of these rather expensive research methods which have to be used on a regular basis regardless of weather conditions and organizational problems is not possible. In addition, these direct methods are difficult to use for technical and technological reasons, and the results are often distorted by the influence of extraneous "noise" and do not correspond to the real picture. One of the methods for predicting flow rates is searching for relations between this parameter and data from geophysical studies, and the use of these relations based on the analogy method.

3. Results and discussion
For the group of seven deposits in the terrigenous reservoirs of the West Siberian oil and gas province, selected on the basis of grouping in [11], satisfactory dependencies were identified by pair correlation between the maximum optimal monthly production of fluid \( Q_{F,max} \) (t/month) and geological, geophysical and technological parameters (at values of the mutual correlation function \( R \geq 0.5 \)), including:
- general \((H_{gen}^D, H_{gen}^N)\), perforated \((H_{perf}^D, H_{perf}^N)\), productive oil saturated \((H_E^D, H_E^N)\) formation thickness;
- average value \((H_P^D, H_P^N)\) of thickness of oil saturated interlayers;
- number of oil saturated interlayers \((n^D, n^N)\);
- sandiness \((K_D^p, K_N^p)\), permeability \((K_{per}^D, K_{per}^N)\) \((10^{-3}\text{um}^2)\), porosity \((m^D, m^N)\)\), oil saturation \((K_N^D, K_N^N\) \((\%))\) coefficients;
- SP relative amplitude \((\alpha_{SP}^D, \alpha_{SP}^N)\);
- formation resistivity by IL \((\rho_{IL}^D, \rho_{IL}^N)\) (Om-m), by a two-meter probe \((\rho_{2,25}^D, \rho_{2,25}^N)\) (Om-m), by LL \((M_{LL}^D, M_{LL}^N)\) (Om-m);
- the distance between the production and injection wells \((F, m)\), where signs D and H characterize the parameters in the production and injection wells, respectively.

Other parameters were not taken into account due to either the absence of their mass determination, or insignificant intervals of their changes.

Values of \(Q_{F}^{\text{max}}\) were determined at the moment of complete cleaning of the bottomhole zone (moment of stabilization of the productivity coefficient) [12], and R was calculated using monthly production and injection time series [13] for each pair of the production and injection wells.

The best dependencies obtained are described by the following functions:

\[
\begin{align*}
q_{F}^{\text{max}_{gen}} &= (r = 0.104); \\
q_{F}^{\text{max}_{perf}} &= (r = 0.250); \\
q_{F}^{\text{max}_{D}} &= (r = 0.189); \\
q_{F}^{\text{max}_{N}} &= (r = 0.298); \\
q_{F} &= (r = 0.137); \\
q_{F}^{\text{max}_{D}} &= (r = 0.109); \\
q_{F}^{\text{max}_{N}} &= (r = 0.355); \\
q_{F}^{\text{max}_{SP}} &= (r = 0.298); \\
q_{F}^{\text{max}_{IL}} &= (r = 0.315); \\
q_{F}^{\text{max}_{D}} &= (r = 0.307); \\
q_{F}^{\text{max}_{N}} &= (r = 0.189); \\
q_{F}^{\text{max}_{gen}} &= (r = 0.197); \\
q_{F}^{\text{max}_{D}} &= (r = 0.190); \\
q_{F}^{\text{max}_{N}} &= (r = 0.247); \\
q_{F}^{\text{max}_{D}} &= (r = 0.263); \\
q_{F}^{\text{max}_{N}} &= (r = 0.187); \\
q_{F}^{\text{max}_{D}} &= (r = 0.129); \\
q_{F}^{\text{max}_{N}} &= (r = 0.254); \\
q_{F}^{\text{max}_{D}} &= (r = 0.299); \\
q_{F}^{\text{max}_{N}} &= (r = 0.302); \\
q_{F}^{\text{max}_{D}} &= (r = 0.217); \\
q_{F}^{\text{max}_{N}} &= (r = 0.173); \\
\end{align*}
\]
it is necessary to know which of them will be affected by the injection and what their fluid flow will be. The low values of the correlation coefficients of the dependences obtained (from 0.104 to 0.355) do not allow for the use of equations (1) - (24) to predict fluid production. Comprehensive analysis of impacts of the parameters under consideration on production was carried out at the second stage using multidimensional regression for different intervals of change in the cross-correlation functions. At \( R < 0.5 \), when there is no influence of injection on the fluid production, the parameters were used only for production wells. The following models were obtained:

- at \( R < 0.5 \):
  \[
  q_F^{\max} = 1014 - 3.358K_{per}^D + 2229\alpha_{sp}^D + 126H_{gen}^D - 240H_A^D + 180N_p^D - 39.8\rho_{L}^D;
  \]
  (25)
- at \( 0.5 \leq R < 0.55 \):
  \[
  q_F^{\max} = 1331 - 4.407K_{per}^D + 2925\alpha_{sp}^D + 165\phi_{gen} \]
  (26)
- at \( 0.55 \leq R < 0.60 \):
  \[
  q_F^{\max} = 1458 - 4.827K_{per}^D + 3204\alpha_{sp}^D + 180N_{gen}^N - 344N_A^N + 259N_p^N - 57.2\rho_{L}^N;
  \]
  (27)
- at \( 0.60 \leq R < 0.65 \):
  \[
  q_F^{\max} = 1584 - 5.247K_{per}^D + 3482\alpha_{sp}^D + 196N_{gen}^N - 374N_A^N + 281N_p^N - 62.2\rho_{L}^N;
  \]
  (28)
- at \( 0.65 \leq R < 0.70 \):
  \[
  q_F^{\max} = 1711 - 5.666K_{per}^D + 3760\alpha_{sp}^D + 212N_{gen}^N - 404N_A^N + 304N_p^N - 67.2\rho_{L}^N;
  \]
  (29)
- at \( 0.70 \leq R < 0.75 \):
  \[
  q_F^{\max} = 1838 - 6.086K_{per}^D + 4039\alpha_{sp}^D + 228N_{gen}^N - 434N_A^N + 326N_p^N - 72.1\rho_{L}^N;
  \]
  (30)
- at \( 0.75 \leq R < 0.80 \):
  \[
  q_F^{\max} = 1965 - 6.506K_{per}^D + 4318\alpha_{sp}^D + 243N_{gen}^N - 464N_A^N + 349N_p^N - 77.1\rho_{L}^N;
  \]
  (31)
- at \( 0.80 \leq R < 0.85 \):
  \[
  q_F^{\max} = 2091 - 6.926K_{per}^D + 4597\alpha_{sp}^D + 259N_{gen}^N - 494N_A^N + 371N_p^N - 82.1\rho_{L}^N;
  \]
  (32)
- at \( 0.85 \leq R < 0.90 \):
  \[
  q_F^{\max} = 2218 - 7.346K_{per}^D + 4875\alpha_{sp}^D + 275N_{gen}^N - 524N_A^N + 394N_p^N - 87.1\rho_{L}^N;
  \]
  (33)
- at \( 0.90 \leq R < 0.95 \):
  \[
  q_F^{\max} = 2345 - 7.765K_{per}^D + 5153\alpha_{sp}^D + 290N_{gen}^N - 554N_A^N + 416N_p^N - 92.0\rho_{L}^N;
  \]
  (34)
- at \( 0.95 \leq R < 1.00 \):
  \[
  q_F^{\max} = 2472 - 8.185K_{per}^D + 5433\alpha_{sp}^D + 306N_{gen}^N - 584N_A^N + 439N_p^N - 97.0\rho_{L}^N.
  \]
  (35)

The multiple correlation coefficients of the models vary from 0.62 to 0.85, i.e. they are quite high and can be used for practical purposes.

For example, when brining idle wells into operation or when transferring them from another horizon, it is necessary to know which of them will be affected by the injection and what their fluid flow will be. Based on the specific situation, specific wells are put into operation.

To determine the impact of injection or well production, the following algorithm was developed:
- for each pair of wells (production - injection) by values $H^D_W$, $K^D_{per}$, $\rho^D_{Il}$, $N^N_E$, $K^N_{per}$, $\rho^N_{Il}$, $F$ the waterflooding efficiency $P_{we}$ is calculated by formula presented in [13]. If $P_{we} \geq P_{we}^{min} = 0.45$ um$^3$·Om$^2$·m$^{-3}$, the production well is affected by the injection well. By formula in [13], the value of the correlation function is calculated and one of the models (26)–(35) is selected. Using this model, the value of the maximum optimal monthly oil production rate is calculated.

If $P_{we} < P_{we}^{min} = 0.45$ um$^3$·Om$^2$·m$^{-3}$, values of the canonical variables $\gamma_1$ and $\gamma_2$ are calculated and location of points in the axes of these variables are determined [13]. When the calculated value falls into the region where $R \geq 0.5$, the above calculations are carried out. At $R < 0.5$, the value of the maximum optimal monthly production is calculated using formula (25).

- using the results obtained, a control decision is made based on the user's settings.

In the conditions of the wells of the objects of group 2 [9], the best dependencies are described by the following functions:

\[
q_{f}^{\max}_{\text{gen}} = (r = 0.018); \\
q_{f}^{\max}_{\text{per}} = (r = 0.090); \\
q_{f}^{\max}_{A} = (r = 0.186); \\
q_{f}^{\max \ln N^D_p} = (r = 0.461); \\
q_{f}^{\max } = (r = 0.178); \\
q_{f}^{\max D} = (r = 0.070); \\
q_{f}^{\max 5.06+12.0 \times 10^{-3} K^D_{PER}} = (r = 0.802); \\
q_{f}^{\max P_5} = (r = 0.703); \\
q_{f}^{\max D_{IK}} = (r = 0.512); \\
q_{f}^{\max D_{BK}} = (r = 0.252); \\
q_{f}^{\max N} = (r = 0.122). 
\]

Significant dependencies are the maximum optimal monthly production of fluid, the average thickness of oil-saturated interlayers, the permeability coefficient, the relative IL amplitude and the IL formation resistance.

The comprehensive analysis of the influence of the parameters under consideration on fluid production made it possible to obtain the following models:

- at $R < 0.5$:

\[
q_{f}^{\max} = 163 + 7.74 N^D_A - 24.5 n^D + 0.51 K^D_{per} + 23.3 \rho^D_{Il} - 4.86 K^D_N; \\
\]

- at $0.5 \leq R < 0.55$:

\[
q_{f}^{\max} = 171 + 8.13 N^D_E - 25.7 n^D + 0.54 K^D_{per} + 24.5 \rho^D_{Il} - 5.10 K^D_N; \\
\]

- at $0.55 \leq R < 0.60$:

\[
q_{f}^{\max} = 187 + 8.90 N^D_E - 28.2 n^D + 0.59 K^D_{per} + 26.8 \rho^D_{Il} - 5.87 K^D_N; \\
\]

- at $0.60 \leq R < 0.65$:

\[
q_{f}^{\max} = 204 + 9.68 N^D_A - 30.6 n^D + 0.64 K^D_{per} + 29.1 \rho^D_{Il} - 6.08 K^D_N; \\
\]

- at $0.65 \leq R < 0.70$:

\[
q_{f}^{\max} = 220 + 10.45 N^D_A - 33.1 n^D + 0.69 K^D_{per} + 31.4 \rho^D_{Il} - 7.29 K^D_N; \\
\]

- at $0.70 \leq R < 0.75$:

\[
q_{f}^{\max} = 236 + 11.2 N^D_A - 35.5 n^D + 0.74 K^D_{per} + 33.8 \rho^D_{Il} - 7.05 K^D_N; \\
\]

- at $0.75 \leq R < 0.80$: 

\[
q_{f}^{\max} = 252 + 12.0 N^D_A - 37.9 n^D + 0.79 K^D_{per} + 36.1 \rho^D_{Il} - 6.80 K^D_N; \\
\]
\[ q_{E}^{\text{max}} = 253 + 12,0n_{E}^{D} - 38,0n_{E}^{D} + 0,79K_{\text{per}}^{D} + 36,1\rho_{IL}^{D} - 7,53K_{N}^{D}; \]  
\[ q_{E}^{\text{max}} = 269 + 12,8n_{A}^{D} - 40,4n_{E}^{D} + 0,84K_{\text{per}}^{D} + 38,4\rho_{IL}^{D} - 8,02K_{N}^{D}; \]  
\[ q_{E}^{\text{max}} = 285 + 13,5n_{A}^{D} - 42,9n_{E}^{D} + 0,89K_{\text{per}}^{D} + 40,8\rho_{IL}^{D} - 8,51K_{N}^{D}. \]  
When changing the maximum values of the mutual correlation functions from 0.5 to 0.9:

\[ q_{E}^{\text{max}} = (326 + 15,48n_{E}^{D} - 49n_{D}^{E} + 1,02K_{\text{per}}^{D} + 46,6\rho_{IL}^{D} - 9,72K_{N}^{D}) \cdot (1,070 + +0,003K_{\text{per}}^{D} - 0,009M_{IL}^{N} + 0,010n_{gen}^{N} + 0,016n_{E}^{N} + 0,044n_{E}^{N} - -0,024m^{N} - 0,036\rho_{IL}^{N} + 0,004K_{N}^{N} - 0,0002F). \]  

The results obtained can be used, for example, when selecting foci for the injection of water into the reservoir by transferring production wells to injection ones.

The algorithm for solving this problem is as follows:
- for each pair of wells (production – injection) by values of \( N_{A}^{D}, K_{\text{per}}^{D}, N_{A}^{N}, K_{\text{per}}^{N}, F \) the water flooding efficiency parameter is calculated by formula [13]
  - if \( P_{we} \geq P_{we}^{\text{min}} = 4.6 \cdot 10^{-3} \) \( \text{um}^{-1} \cdot \text{Om}^{-2} \cdot \text{m}^{-1} \), the production well will experience the influence of injection, and the value of the mutual correlation function is calculated by the formula which shows the degree of influence of injection on production. One of the models (48) - (55) is selected by the value of the cross-correlation function, and the value of the maximum optimal monthly fluid production is calculated;
  - if \( P_{we} < P_{we}^{\text{min}} \), equation [13] is used to calculate the value of canonical variable \( y_{i} \). At \( y \geq 0 - R \geq 0.5 \) calculations presented above are carried out [13]. At \( y < 0 - R < 0.5 \), the values of the maximum optimal monthly fluid production are calculated by formula (47);
- after the flow rates of the production wells surrounding the focal injection were analyzed, the conclusion about the water injection is drawn.

4. Conclusion
Based on the research results mathematical models were built, and the method for predicting potential flow rates using indirect information when developing deposits in normal modes and using artificial waterflooding was developed. An algorithm for substantiating selective and focal waterflooding, transfer of wells from other horizons and transfer of idle wells into the productive well stock was developed. The factors that have a major impact on the flow rates of wells in various geological and field conditions were identified. Physical interpretation of their influence was given.

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