Comparative Analysis of the Method for Predicting the Inflow to an Oil Well with a Wavy Profile

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Abstract. This paper discusses approaches to calculating the productivity of oil wells. Existing solutions do not allow taking into account many important factors, such as, for example, hydraulic resistance in the wellbore, wellbore trajectory, etc. The article presents a developed numerical method for modeling oil flow to an oil well with a complex wellbore trajectory along the productive formation. Based on the function for the point flow potential and the method of hydraulic calculations, an original solution was obtained, which takes into account not only the change in pressure and flow rates for individual sections of the well, but also the hydrodynamic imperfection of the well.

1. Introduction

In the USSR, the search for technical solutions for the construction of wells with a complex profile in the productive formation began in 1949. A.M. Grigoryan, V.A. Bragin and K.A. Tsarevich. When they are applied, well production rates multiply, the drainage zone area and the oil recovery factor increase [1]. Currently, the development of fields using wells of complex geometry is an urgent direction in the development of the oil industry. To increase the area of the collector opening, the technology of artificial curvature of the trajectory of the horizontal end is used with the help of rotary controlled systems. Figure 1 shows the Well layout with horizontal completion with two cycles of undulating profile [2].

![Flow direction](image)

**Figure 1.** A horizontal well to the well with two wave-shaped cycles.
Such a design of the horizontal end may be due to the need to open up layered formations with frequent interlayering of sandstones and clay bridges.

2. Methods
At present, analytical formulas are known for determining the specific flow rate of well sections with horizontal completion. In the work of A.S. Samoilov [1] considered the effect of increasing the length of the wellbore, open flow on the growth of hydraulic losses and a decrease in drawdown in the direction of the end of the horizontal wellbore. Consider the dependencies that allow simulating the flow to an open wellbore of complex geometry. F.N. Domanyuk proposes to model an open wellbore with a chain of spheres in [3].

Figure 2. Schematization of the trajectory of the sinusoidal well:
1 - trajectory of a complex well; 2 - simplified trajectory.

For the calculation, we will use the equation for the fluid flow to the undulating well with an arbitrary number of cycles F.N. Domanyuk [2]:

$$Q = \frac{2\pi kh}{\mu B} \left( P_e - P_w \right) \left[ \ln \left( \frac{\pi e R_1}{2L \sin \varphi} \right) + \frac{h}{L} \ln \left( \frac{2h \sin \varphi}{\pi e (1 + \gamma) r_w} \right) \right]$$

(1)

where: $\gamma = \left( \frac{h - \rho \cdot \cos \varphi}{4h} \right)^{0.5}$, $k$ is the absolute permeability of the reservoir, $m^2$; $h$ is the thickness of the reservoir, $m$; $\mu$ is the oil viscosity, $Pa \cdot s$; $B$ - volumetric coefficient of oil; $P_e$ - reservoir pressure, $Pa$; $P_w$ - well pressure, $Pa$; $R$ - radius of the feed loop, $m$; $\rho$ - length of one inclined section, $m$; $\varphi$ - angle of inclination of a straight section, $deg$; $L$ - well length, $m$; $r_w$ - well radius, $m$.

To calculate the flow rate of undulating well (1), we will take the following data:

$k = 2,96 \cdot 10^{-14} m^2$, $h = 40 m$, $\mu = 0,005 Pa \cdot s$, $B = 1$, $P_e = 18,5 MPa$, $P_w = 15 MPa$, $R = 400 m$, $\rho = 304 m$, $\varphi = 83^\circ$, $L = 762 m$, $r_w = 0,1 m$.

$$\gamma = \left( \frac{40 - 304 \cdot \cos \varphi}{4 \cdot 304} \right)^{0.5} = 0,1599$$

$$Q = \frac{2 \cdot \pi \cdot 2,96 \cdot 10^{-14}}{0,005 \cdot 1} \left( \frac{18,5 - 15}{10^6} \right) \cdot 10^6 \left[ \ln \left( \frac{\pi e \cdot 400}{2 \cdot 762 \cdot \sin \varphi} \right) + \frac{40}{762} \ln \left( \frac{2 \cdot 40 \cdot \sin \varphi}{\pi e \left( 1 + 0,1599 \right) \cdot 0,1} \right) \right] = 430 m^3/day$$

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The well flow rate, calculated using the analytical formula, was 430 m³/day.

Many researchers [2-6] note that the inflow profile along the horizontal well has a U-shape. Knowing the flow rates of individual sections allows you to evaluate the effect of interference on other sections of the wellbore, taking into account the distance between sections and their productivity, as well as take into account interference from adjacent wells.

To solve the problem described above, we divide the open hole into many sections, the length of each of which is much less than the length of the wellbore, and determine the flow rate of each section, taking into account its interference with the rest. Let us represent the elementary section of the borehole dl as a point flow, to which there is a radial-spherical inflow. Then the straight section of finite length is the drain line.

![Diagram of a horizontal wellbore divided into straight sections](image)

**Figure 3.** Representation of the trajectory of the sinusoidal well in the form of a sequence of straight-line areas.

Representing the trajectory of the wellbore as a set of sequentially located rectilinear sections (drain lines), calculating the angle α with the vertical of each section of length l, we obtain an expression for the depression drop in the reservoir (a detailed derivation of the formulas is given in [7]):

\[
\Delta P_j = \sum_{i=1}^{N} Q_i S_{ij}
\]

\[
S_{ij} = \frac{\mu}{4\pi k_{eq}} \int_0^l \sum_{n=\pm\infty} \sqrt{\chi \left(\left(x_{j-1} + \frac{l}{2}\sin(\alpha)\right) - (x_{i-1} - L\sin(\alpha))\right)^2 + \chi \left(z_{j-1} + \frac{l}{2}\cos(\alpha)\right) - (z_{i-1} + L\cos(\alpha)) + 2nh} \, dl
\]

\[
+ \sqrt{\chi \left(\left(x_{j-1} + \frac{l}{2}\sin(\alpha)\right) - (x_{i-1} - L\sin(\alpha))\right)^2 + \chi \left(z_{j-1} + \frac{l}{2}\cos(\alpha)\right) + (z_{i-1} + L\cos(\alpha)) + 2nh} \, dl
\]

\[
- 0.5 \sqrt{\chi \left(\left(x_{j-1} + \frac{l}{2}\sin(\alpha)\right) - (x_{i-1} - L\sin(\alpha))\right)^2 + \chi \left(z_{j-1} + \frac{l}{2}\cos(\alpha)\right) - (z_{i-1} + L\cos(\alpha)) + 2nh} \, dl
\]
The well trajectory through the reservoir is represented by a sequence of drain lines found on the wall of each section as a superposition of the pressures created by the work of all sections. The system of equations for the distribution of pressure in the reservoir during the operation of \( N \) sections can be expressed as:

\[
\begin{align*}
-0.5 & \left\{ \frac{1}{(x_{i-1} + \frac{L}{2} \sin(\alpha_j))} \left[ \left( x_{i-1} - L \cdot \sin(\alpha_j) \right)^2 + \frac{1}{R_c^2} \left( z_{i-1} + \frac{L}{2} \cos(\alpha_j) \right) + \left( z_{i-1} + L \cdot \cos(\alpha_j) \right) + 2nh \right]^2 \right\} - \\
-0.5 & \left\{ \frac{1}{(x_{i-1} + \frac{L}{2} \sin(\alpha_j))} \left[ \left( x_{i-1} - L \cdot \sin(\alpha_j) \right)^2 - \frac{1}{R_c^2} \left( z_{i-1} + \frac{L}{2} \cos(\alpha_j) \right) - \left( z_{i-1} + L \cdot \cos(\alpha_j) \right) + 2nh \right]^2 \right\} - \\
-0.5 & \left\{ \frac{1}{(x_{i-1} + \frac{L}{2} \sin(\alpha_j))} \left[ \left( x_{i-1} - L \cdot \sin(\alpha_j) \right)^2 - \frac{1}{R_c^2} \left( z_{i-1} + \frac{L}{2} \cos(\alpha_j) \right) + \left( z_{i-1} + L \cdot \cos(\alpha_j) \right) + 2nh \right]^2 \right\} dL
\end{align*}
\]

where \( h \) is the thickness of the reservoir, \( m; \ X_h = \sqrt{k_h / k_h} \) - anisotropy in the horizontal direction; \( \chi_v = \sqrt{k_v / k_v} \) - anisotropy in the vertical direction; \( x, y, z \) - coordinates of straight-line sections of the wellbore, \( m; \ R \) - radius of the feed loop, \( m \).

To determine the flow rates of the wellbore sections (inflow profile), it is necessary to jointly solve the system of equations for the distribution of pressure in the reservoir during the operation of \( N \) sections and the equation for the developing fluid flow in the wellbore. The pressure in the reservoir will be found on the wall of each section as a superposition of the pressures created by the work of all sections. The movement of fluid through the well is described by the Bernoulli equation:

\[
\rho g z_0 + P_0 + \frac{\rho V^2}{2} = \rho g z_n + P_n + \frac{\rho V^2}{2} + \rho g \sum h,
\]

\( \rho g \sum h \) - pressure loss, when the fluid moves between points b and a, Pa; \( V \)- fluid velocity, m/s.

Finally, we have a system of equations, solving which with respect to \( Q \) we find the flow rate of each section:

\[
\begin{align*}
Q_1S_{1,1} + Q_2S_{2,1} + \ldots + Q_NS_{N,1} &= \Delta P_a - \frac{\rho}{2} \left( V^2_n - V^2_1 \right) - \rho g \sum (h_{mp})_1 \\
Q_1S_{1,2} + Q_2S_{2,2} + \ldots + Q_NS_{N,2} &= \Delta P_a - \frac{\rho}{2} \left( V^2_n - V^2_2 \right) - \sum_{k=1}^{N} \rho g (h_{mp})_k \\
Q_1S_{1,j} + Q_2S_{2,j} + \ldots + Q_NS_{N,j} &= \Delta P_a - \frac{\rho}{2} \left( V^2_n - V^2_j \right) - \sum_{k=1}^{N} \rho g (h_{mp})_k \\
Q_1S_{1,N} + Q_2S_{2,N} + \ldots + Q_NS_{N,N} &= \Delta P_a - \frac{\rho}{2} \left( V^2_n - V^2_N \right) - \sum_{k=1}^{N} \rho g (h_{mp})_k
\end{align*}
\]

We will accept the initial data similar to those used in the calculation according to the formula of F.N. Domanyuk (1). The well trajectory through the reservoir is represented by a sequence of drain lines.
Wellbore intervals located in the middle of sections with a zenith angle of 90 ° and close to the boundaries of the formation give lower production rates, while those located in the straight section and in the middle of the formation operate at higher productivity.

3. Results and discussion
Consider a horizontal oil well with a wavy end at a depth of 2000 m, with a formation thickness of 40 m in the TNavigator software package. Set the number of grid cells in the X - 100, Y - 10, Z - 41 directions, with the X - 10 m, Y - 60 m, Z - 1 m dimensions, the total number of active blocks - 41000. The MULTPV keyword is a multiplier pore volume for the extreme faces of the reservoir model, calculated by the simulator from block markings. The permeability value is taken to be equal in all cells and in all directions X, Y, Z - 30 mD, in the properties of degassed oil we set the required viscosity and pressure in the oil phase. Since the system is single-phase, the relative permeability to water in the RPT table will be zero. The OWC level is set at a depth of 2160 m.

The well flow rate, calculated using the tNavigator software package, was 342 m³/day.

To assess the effect of taking into account additional parameters of a wave-like well, such as the profile trajectory in the reservoir, the effect of the proximity of impermeable boundaries (top and bottom), uneven distribution of the inflow profile along the wellbore, hydraulic resistance, calculations were performed using the Borisov [8] and Joshi [9] for a horizontal termination of the same length, passing through the middle of the formation. A summary table based on the calculation results is shown in Table 1.
Table 1. Comparison of calculated inflow.

| Formula               | Borisov (horizontal well) | Joshi (horizontal well) | Domanyuk | Sokhoshko-Kolev | Numerical model tNavigator |
|----------------------|---------------------------|-------------------------|----------|-----------------|---------------------------|
| well flow rate, m³/day | 446                       | 445                     | 430      | 342             | 342                       |

4. Conclusion
On the basis of analytical formulas, calculations of the flow rate of a well with a wavy profile in an isotropic formation were performed, a numerical-analytical solution and numerical modeling were carried out, which give similar results of calculating the fluid inflow.

The established difference of 20% when comparing the analytical and numerical solution of the problem, shows that the simplified formula can be used for the rapid assessment of the productivity of a well with a wavy profile. The overestimation of the values obtained by the Borisov and Joshi formulas is explained by the fact that the position of the wellbore when deriving the formula was taken by the authors in the middle of the productive formation, while the sections of the wellbore with a wavy profile near the top and bottom work with lower production rates.

5. References
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