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Description of steady inflow of fluid to wells with different configurations and various partial drilling-in

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There are many equations of steady inflow of fluid to the wells depending on the type of well, presence or absence of artificial or natural fractures passing through the well, different degrees of drilling-in of the wellbores. For some complex cases, analytical solutions describing the inflow of fluid to the well have not yet been obtained. An alternative to many equations is the use of numerical methods, but this approach has a significant disadvantage – a considerable counting time. In this regard, it is important to develop a more general analytical approach to describe different types of wells with different formation drilling-in and presence or absence of fractures.

Creation of this method is possible during modeling of fractures by a set of nodes-vertical wells passing from a roof to floor, and modeling of a wellbore (wellbores, perforation) by a set of nodes – spheres close to each other. As a result, based on this approach, a calculation algorithm was developed and widely tested, in which total inflow to the well consists of the flow rate of each node taking into account the interference between the nodes and considering the impermeable roof and floor of the formation. Performed modeling confirmed a number of known patterns for horizontal wells, perforation, partial drilling-in of a formation, and also allowed solving a number of problems.

***Key words*:** spherical flow; radial flow; steady filtration; wells; fracture; partial drilling-in; perforation

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Introduction. Currently, various types of wells are used in the oil industry: vertical, directed, horizontal, multilateral horizontal, horizontally branched. Partial drilling-in of the formation is often present and hydraulic fracturing is carried out in all of these types. Situation is further aggravated by the fact that roof and floor of the formation can be both impermeable and have constant pressure (gas cap, bottom water). As a result, we get a huge set of analytical dependencies for solving the problems of steady and unsteady fluid inflow to the well. In some complex cases, there are no analytical formulas for calculating the inflow: winding wellbores; partial drilling-in of the formation and a fracture passing through the well; inflow to perforation area; horizontal wells (HW) with multiple fractures of different lengths and at different angles; wells with complex partial drilling-in and others.

Numerical modeling is usually carried out for them that has one big drawback – a large calculation time, as a result of which the solution of inverse hydrodynamic problems is significantly complicated.

In addition to the linear law of filtration (Darcy), there are more complex filtration laws – quadric; power-law; with an initial pressure gradient; taking into account the dependence of the formation permeability on pressure, etc. But even for one type of well and one law of filtration, there are several equations of steady inflow. For example, Polubarinova-Kochina P.Ya., Merkulov V.P., Tabakov V.P., Borisov Yu.P., Pilatovskii V.P., Griguletsky V.G., Nikitin B.A., Joshi S.D, Economides M.J, Ehlig-Economides C.A, Giger F.M, Babu D.K, Odeh A.S, Raghavan R., Butler R.M, Suprunowicz R., Fazlyev R.T., Lysenko V.D. , Khairullin M.Kh., Mukminov I.R., Berdin T.G., Aliev Z.S., Zolotukhin A.B. and others devoted their works to determining the HW production rate for the linear filtration law [1-10, 12-18]. The same is with other types of wells. Exception is a perfect vertical well with a circular feed contour, for which the linear Dupuit equation is used with the linear filtration law.

Presence of several formulas for one type of well instead of one can only indicate a different degree of idealization and, accordingly, error in solving the problem. In this regard, there are many dissertations and works devoted to the comparison of various formulas, as well as the search for new solutions for special cases.

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However, the most correct approach is to create and use the minimum number of calculation methods or one method for calculating well inflow for a given filtration law. Moreover, it is feasible to have such a method not only for each type of well, but also for all possible types of wells with different methods of drilling-in. Additionally, we add a solution to the problem for non-stationary filtration. This work is dedicated to this purpose.

Inflow to wells with horizontal endings with different configuration of boreholes and various partial drilling-in. The most common calculation method for wells with horizontal endings (WHE) without using numerical methods refers to the previous solution, when the initial three-dimensional problem is reduced to two flat problems [7, 15]: in the vertical plane – to the inflow of fluid to the point drain in a strip with an impenetrable roof and floor, in the horizontal – to the inflow to the fracture between roof and floor.

Fracture was modeled by a set of vertical wells or nodes that are close enough to each other. This approach allowed describing the inflow of fluid to the drain, which is a curved vertical fracture passing through the entire thickness of the formation. Production rates of nodes Q_i in the horizontal plane were determined when solving a system of equations that takes into account the interference of nodes:

$$\begin{aligned} Q_1 &= \frac{2\pi\varepsilon}{\ln R_k/r_w}\left(\left[P_f + \frac{1}{2\pi\varepsilon}\sum_{j=1}^{n} Q_j \ln\frac{r_{1j}}{R_k}\right] - P_{bi}\right) \\ Q_i &= \frac{2\pi\varepsilon}{\ln R_k/r_w}\left(\left[P_f + \frac{1}{2\pi\varepsilon}\sum_{j=1}^{n} Q_j \ln\frac{r_{ij}}{R_k}\right] - P_{bi}\right), \\ Q_n &= \frac{2\pi\varepsilon}{\ln R_k/r_w}\left(\left[P_f + \frac{1}{2\pi\varepsilon}\sum_{j=1}^{n} Q_j \ln\frac{r_{nj}}{R_k}\right] - P_{bi}\right) \end{aligned} \quad (1)$$

where Q_j – node flow rate, P_f – formation pressure; P_b – bottomhole pressure; r_w – well radius, R_k – contour radius, r_{ij} – distance between nodes, ε – formation hydraulic conductivity.

Difference between fracture and WHE primarily lies in the appearance of additional filtration resistances for WHE. Several equations are known that allow taking into account the convergence of streamlines to the WHE wellbore (see the table).

Equations that take into account the convergence of streamlines to the WHE wellbore for impermeable roof and floor of the formation

Author	Equation
Joshi S.D.	$Q_r = \frac{2\pi k L \Delta P/\mu}{\ln\left(\frac{h}{2r_w}\right)}$
Borisov Yu.P., Pilatovskii V.P., Tabakov V.P.	$Q_r = \frac{2\pi k L \Delta P/\mu}{\ln\left(\frac{h}{2\pi r_w}\right)}$
Butler R.M. (for eccentric location of the wellbore)	$Q_r = \frac{2\pi k L \Delta P/\mu}{\ln\left(\frac{h}{2\pi r_w}\sin\frac{\pi Z_W}{h}\right)}$ for $Z_w > 3r_w$

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End of the table

Author	Equation
Butler R.M. (general equation)	$\Delta P = \frac{Q_r \mu}{4\pi k L}\left\{\ln\left(ch\frac{2\pi x}{h}-1\right)-\ln\left(ch\frac{2\pi r_w}{h}-1\right)\right\}$
Butler R.M. (for anisotropic formation)	$Q_r = \frac{2\pi k_h L\,\Delta P/\mu}{\frac{h^*}{h}\ln\left(\frac{h^*}{2\pi r_w^*}\right)}$, where $h^* = h\beta$, $r_w^* = 0{,}5 r_w(1+\beta)$, $\beta = \sqrt{k_h/k_v}$
Mukherjee H., Economides M.J.	$Q_r = \frac{2\pi k_h L \Delta P/\mu}{\frac{h^*}{h}\ln\left(\frac{h^*}{2r_w}\right)}$
Domanyuk F.N., Zolotukhin A.B. (for a HW at an angle φ to the vertical plane)	$Q_r = \frac{2\pi k L\,\Delta P/\mu}{\beta\ln\left(\frac{2\beta h}{\pi\varepsilon\left(1-2\delta^2/h^2\right)r_w}\sin\varphi'\right)}$, where $\beta = \sqrt{k_h/k_v}$, $\varphi' = arctg(tg\varphi/\beta)$

Note. Q_r – flow rate when modeling in a vertical plane, $\beta = \sqrt{k_h/k_v}$ – parameter of anisotropy for formation permeability, L – total wellbores length, δ – distance from the center of the wellbore to the median plane of the formation.

To calculate the well flow rate, filtration resistances are summed in the vertical and horizontal planes. This approach made it possible to take into account any configuration of horizontal wellbores and the location of working sections. Problem is solved for steady and unsteady fluid flow in the formation. At the same time, an external model for the Saphir software was created and tested. Unfortunately, the scope of this calculation method is associated only with small-thickness formations, and more precisely, with a small ratio of the formation thickness to the length of the HW wellbore. First of all, this is caused by an approximate consideration of the filtration resistance when describing various equations of inflow in the vertical plane to the HW wellbore between an impermeable roof and floor of the formation.

Implementation of a spherical flow to describe a three-dimensional fluid current. The most common solution can be obtained using a three-dimensional fluid flow to the well. This is achieved by introducing a spherical flow to the nodes simulating the wellbore of any well (Fig.1). This idea is not new, the approach was described back in the 90s of the last century by Ozkan E., Raghavan R. [17], who, on the basis of this approach, developed a number of solutions for various types of flows and formation boundaries. In Russia, Domanyuk F.N. and Zolotukhin A.B. worked in this regard [5, 6]. They proposed an approximation of the infinite sums that arise when modeling the roof and floor by the method of displaying drains, using approximate analytical dependencies.

Nobody used a direct solution to the problem with summarizing from $-\infty$ to $+\infty$ to account for impermeable roofs and floors. Although this particular approach would allow describing the inflow of fluid to the well with any configuration of the wellbores. Instead, various simplifications of the problem were used, and a number of solutions by Ozkan E., Raghavan R. also contain infinite sums, but from 1 to $+\infty$.

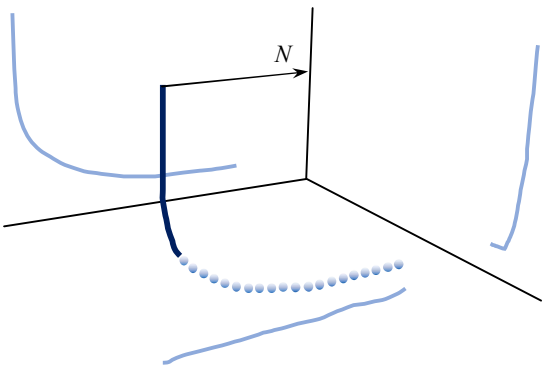


Fig.1. Representation of a wellbore in various configurations by a set of spheres

Therefore, an attempt was made to solve the problem directly, i.e. by using the original equations of inflow to the spheres modeling the wellbore. Proposed algorithm was based on the approach, implemented earlier in solving the system of equations (1), i.e. the problem was solved taking into account the interference of individual nodes. Only in this case, the nodes were not vertical wells as previously for equation (1), but spheres. For this, a system of n equations with n unknown node flow rates is derived:

$$Q_1 = -\frac{4\pi\varepsilon}{\sum\limits_{m=-\infty}^{m=\infty}\alpha_{1m}}\left(\left[P_f - \frac{1}{4\pi\varepsilon}\sum_{j=1}^{n}\left(Q_j\sum_{k=-\infty}^{k=\infty}\alpha_{1k}\right)\right] - P_{bi}\right)$$

$$Q_i = -\frac{4\pi\varepsilon}{\sum\limits_{m=-\infty}^{m=\infty}\alpha_{im}}\left(\left[P_f - \frac{1}{4\pi\varepsilon}\sum_{j=1}^{n}\left(Q_j\sum_{k=-\infty}^{k=\infty}\alpha_{ik}\right)\right] - P_{bi}\right), \quad (2)$$

$$Q_n = -\frac{4\pi\varepsilon}{\sum\limits_{m=-\infty}^{m=\infty}\alpha_{nm}}\left(\left[P_f - \frac{1}{4\pi\varepsilon}\sum_{j=1}^{n}\left(Q_j\sum_{k=-\infty}^{k=\infty}\alpha_{mk}\right)\right] - P_{bi}\right)$$

where

$$\alpha_{im} = \frac{h}{\sqrt{r_w^2 + (-2hm)^2}} + \frac{h}{\sqrt{r_w^2 + (-2hm - 2Z_{wi})^2}} - \frac{h}{\sqrt{R_k^2 + (-2hm)^2}} - \frac{h}{\sqrt{R_k^2 + (-2hm - 2Z_{wi})^2}}; \quad (3)$$

$$\alpha_{ik} = \frac{h}{\sqrt{R_k^2 + (-2hk)^2}} + \frac{h}{\sqrt{R_k^2 + (-2hk - 2Z_{wi})^2}} - \frac{h}{\sqrt{r_{ij}^2 + (-2hk)^2}} - \frac{h}{\sqrt{r_{ij}^2 + (-2hk - 2Z_{wi})^2}}, \quad (4)$$

here h – formation thickness; Z_w – distance from the floor of the formation to the center of the node.

As for the previous calculation algorithm, in this case, using a spherical flow, it is possible to set different bottomhole pressures in nodes, which allows taking into account friction losses and the effect of hydraulic locks in various types of wells.

Algorithm was tested using the created external program for Saphir as follows. Comparing the values of the total flow rates of the nodes for the radial and spherical steady flows, the pseudo-skin effect for HW was calculated. Further, this value was substituted into the previously developed algorithm for interpreting the pressure recovery curve (PRC) [7], and the resulting solution was compared with the Saphir reference solution for special cases – horizontal and vertical wells.

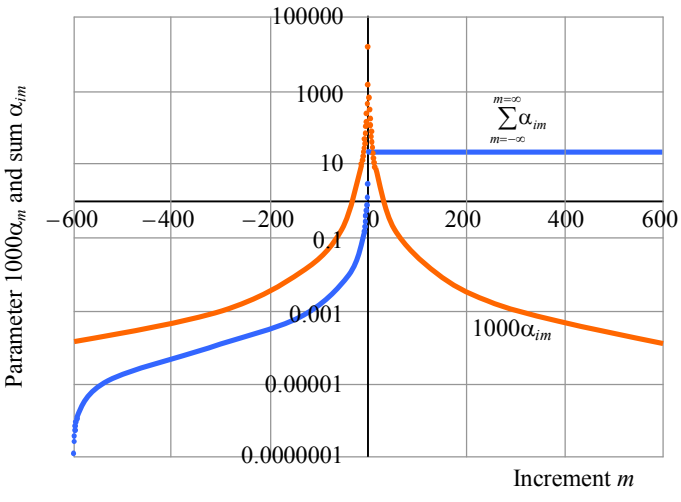


Fig.2. Example of parameters dependence $1000\alpha_{im}$ and $\sum_{m=-\infty}^{m=\infty}\alpha_{im}$ on increment m when summarizing from $-\infty$ to $+\infty$

Finite numbers were used as $-\infty$ and $+\infty$ in the system of equations (2)-(4), and when going beyond their bounds the influence of the following terms is extremely small (Fig.2).

Results of spherical flow simulation. After testing and checking the algorithm, a simulation of WHE was performed, which led to an interesting conclusion. In a homogeneous formation at the same bottomhole pressure without the influence of neighbor-

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ing wells, according to the equation of Butler R.M., inflow to the fracture is a U-shaped profile [7, 13]. Same trend is repeated by the inflow profile calculated by the system of equations (1) using the equations for the radial flow. For a spherical flow, when modeling a HW, end nodes have a much smaller inflow, i.e. U-profile is smoothed out. In particular, for the calculation conditions presented in Fig.3, inflow for the end nodes decreases by more than two times. This can be explained by a smaller inflow to the node-sphere compared to the inflow to the node-vertical well.

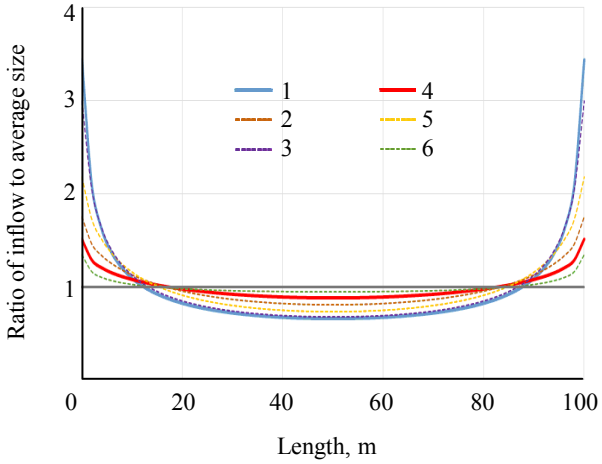


Fig.3. Profile of inflow to fracture (radial flow) and to HW (spherical flow) for various formation thicknesses

1 – radial flow h = 9.144 m; 2 – spherical h/2; 3 – spherical h/10; 4 – spherical h = 9.144 m; 5 – spherical h/4; 6 – spherical 10h

Proximity of the inflow profiles for radial and spherical flows is characteristic only for small formation thicknesses, and more precisely, for a small ratio of thickness to wellbore length (Fig.3). It was noted that for this condition the convergence of system (2)-(4) becomes worse, however, it is quite possible to use the system of equations (1) here. When the ratio of vertical to horizontal permeability is less than 1, $k_z/k_r < 1$, which is typical for most reservoirs, convergence of the system (2)-(4) solution, on the contrary, improves, but due to the need to introduce a more frequent arrangement of nodes, in this case, counting time increases.

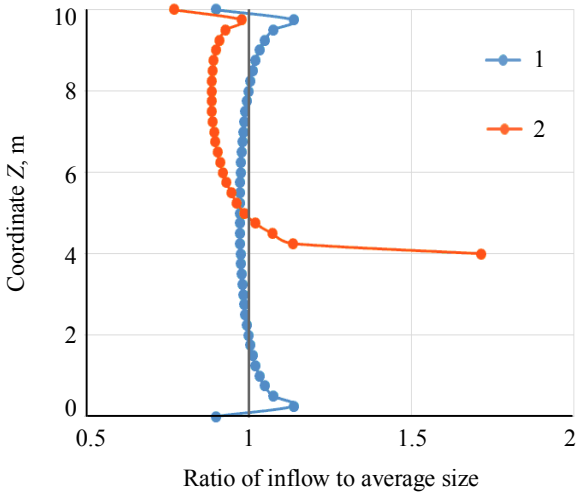


Fig.4. Inflow profile of spherical flow to a perfect vertical well and well with partial drilling-in

1 – perfect well; 2 – partial drilling-in

When testing the algorithm for perfect vertical wells, it was noted that the profile of the inflow due to the error in calculating the sums is not constant, as follows from the equation for the radial flow (Fig.4). End nodes usually have a spread, however, total production rate of the nodes coincides with the flow rate of the well up to the sixth decimal. In addition, during the calculation process, it was noted that frequent partitioning into nodes leads to an unstable solution, and therefore there is a limit on the number of nodes over the thickness of the formation. On average, distance between the nodes should be twice the diameter of the sphere. For a well with partial drilling-in, as expected, the greatest inflow is observed from the side of the outer perforation intervals or end sections of the wellbore, remote from the roof or floor (Fig.4). For the condition $k_z/k_r < 1$, inflow profile to a vertical well with partial drilling-in becomes more even. Disadvantages of the proposed method can only be attributed to the increase in the counting time for low vertical permeability by $1/\sqrt{k_z/k_r}$ times.

Used approach makes it possible to take into account different configuration of the wellbore(s), various working sections of the wellbore(s), changing position of the wellbore relative to the roof and floor, different bottomhole pressures along the length of the wellbore(s) to account for friction losses or the effect of hydraulic locks. For example, HW with multiple hydraulic fractures is modeled by a set of spherical nodes for a wellbore and a set of vertical well nodes for fractures. Principal limitation of the method is its use for weakly compressible fluids, which is due to the use of the superposition method. However, introduction of pressure pseudo-functions instead of pressure al-

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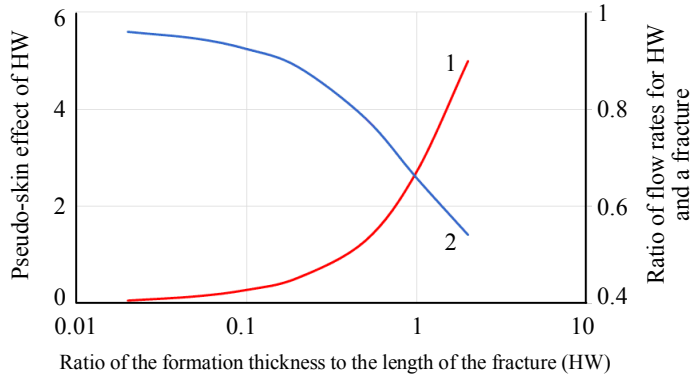


Fig.5. Dependence of the pseudo-skin effect of HW and the ratio of flow rates for HW and a fracture on the ratio of the formation thickness to the length of the fracture (HW)
1 – pseudo-skin effect of HW; 2 – ratio of flow rates

lows obtaining an approximate solution for the motion of gases in the formation. Another condition for the algorithm to work is the need for uniform distribution of nodes for modeling the wellbore.

Calculation of the total flow rates for the nodes-spheres and nodes-vertical wells allows determining the pseudo-skin effect, due to the convergence of streamlines for WHE and directed wells

$$S_{HW} = \frac{1}{\sum_{i=1}^{n} Q_{sph}} - \frac{1}{\sum_{i=1}^{n} Q_{rad}}, \qquad (5)$$

where $\sum_{i=1}^{n} Q_{sph}$ – dimensionless total inflow of nodes-spheres when using a spherical flow for HW; $\sum_{i=1}^{n} Q_{rad}$ – dimensionless total inflow of nodes-vertical wells when using radial flow for a fracture.

In turn, this pseudo-skin effect makes it possible to interpret PRC for a wide variety of well types in the created external program for Saphir.

Comparison of inflow to fracture and HW. Some experts, for example [10], neglect the pseudo-skin effect, and for the WHE they use the solutions, which are obtained for the fracture, while completely ignoring the convergence of the lines to the point drain in the strip between the impermeable roof and floor. However, this difference may be significant. Calculation results presented in Fig.5 confirm that the fracture flow rate is always higher than the flow rate of HW, and this difference increases with small lengths of the fracture (HW) or large ratios of the formation thickness to the length of the wellbore (fracture) h/L. Pseudo-skin effect, as expected, increases with h/L. If the formation is anisotropic, then instead of the relation h/L (Fig.5) parameter $h/\left(L\sqrt{k_z/k_r}\right)$ should be used, which is usually larger than h/L. In this regard, relevance of taking into account the difference between HW and the fracture increases for anisotropic formation.

Inflow to perforation interval. It is widely known that the methods of primary and secondary drilling-in of formations have a significant impact on the productive characteristics of the well. Imperfection of vertical wells by degree of drilling-in was already considered in the works of Musket M., Kozeni I., Schurov V.I., Charny I.A., Pirvedyan A.M., Glagovsky M.M., Hein A.T. In general, as Charny I.A. notes, the solution for the problem of the formation with partial drilling-in is a significant challenge due to the need to solve an infinite number of equations with an infinite number of unknowns. Therefore, in most cases, authors resort to various simplifications or use the method of electrohydrodynamic analogy (EHDA). Even more complex are the problems of determining additional filtration resistances due to imperfection of the well by degree of drilling-in, i.e. due to the presence of perforation [11].

The proposed method allows taking into account various partial drilling-in for vertical, directional wells and WHE. Additionally, it is possible to describe the inflow to the perforation interval of the well. To do this, it is necessary to present the interval in the form of nodes-spheres set with the diameter of the perforation. Performed abstract modeling of perforation confirmed a significant effect on the productive characteristics of the well (Fig.6-7): anisotropy coefficient, fraction of shot or drilled formation thickness, distance between perforation, diameter of perforation.

Obtained patterns are not new and were received previously by various authors. Principal difference of this work is the possibility of direct calculation of inflow to perforation by analytical dependences for a wide variety of options instead of using empirical formulas, numerical simulations, or EHDA results. In this regard, this method has great potential in comparison with known methods.

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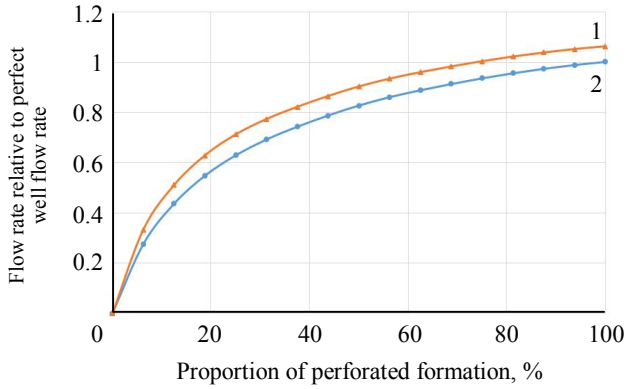


Fig.6. Influence of the perforation length *l* and the proportion of the shot formation thickness on well flow rate

1 – *l* = 0.3 m; 2 – *l* = 0.2 m

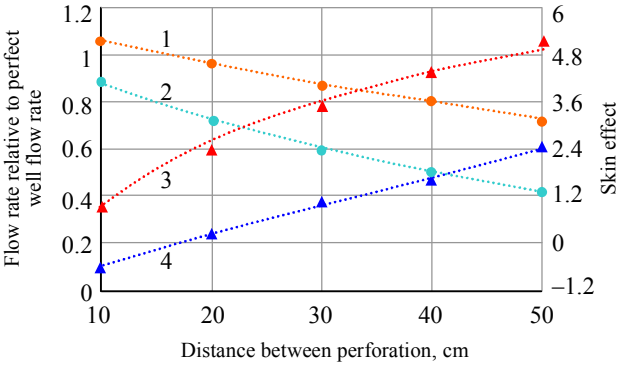


Fig.7. Influence of distance between perforation and formation anisotropy on well flow rate and skin effect

Flow rate: 1 – *kz*/*kr* = 1; 2 – *kz*/*kr* = 0.1
Skin effect: 3 – *kz*/*kr* = 0.1; 4 – *kz*/*kr* = 1

Calculation results (Fig.6, 7) are presented in relation to the flow rate of a perfect well. In order to reduce the error in determining this parameter, taking into account the different diameters of the borehole and perforation, a perfect vertical well was modeled by specifying nodes-vertical wells passing along the perimeter of the well cross-section with a diameter equal to the diameter of the perforation.

Ratio of the flow rate of an imperfect well to the flow rate of a perfect well is essentially a RP parameter (ratio of actual productivity to potential), provided the depression is constant. Component of the skin effect due to the perforation is different depending on the hydraulic conductivity of the formation.

In general, use of this approach allows isolating a component from the total skin effect and in this regard, more accurately calculate the skin effect itself, due to the changed properties of the bottomhole zone or the presence of fracture (fractures) passing through the wellbore. In commercial programs, for example, Saphir [14], only partial drilling-in is taken into account, but perforation is not considered. Therefore, using proposed approach allows refining the skin effect.

Obtained data show that flow rate of the well can be both higher and lower than the flow rate of a perfect well. This trend primarily depends on coefficient of anisotropy, density of perforation per meter of formation thickness, length of the perforation. Most often, imperfection by the characteristic of the drilling-in is precisely imperfection, i.e. additional filtration resistance. However, under favorable conditions, perforation can reduce filtration resistance compared to a perfect well, i.e. improve skin effect and RP parameter. This leads to the obvious conclusion about the need to increase length and diameter of perforation. For this, various attempts are made to use RadTech radial perforation technology and the use of drilling perforators, but the solution to this problem is far from perfect.

Inflow profile to the nodes-spheres modeling the perforation is of particular interest. As expected, the main inflow is characteristic for ends of the perforation or the nodes farthest from the well. This pattern was previously discovered for HW and MHW by various authors, including our early studies [7]. In this regard, in a homogeneous formation it is recommended to perforate intervals as far as possible from each other in order to reduce their mutual influence.

The highest inflow at the ends of the perforation allows explaining quite acceptable values of RP parameter and skin effect from hydrodynamic investigations with a clear deterioration in the properties for a certain zone of the formation after initial drilling-in, which is observed from petrophysical investigations. Reason is that when the perforation goes beyond the limits of degraded properties of the formation, it does not matter what proportion of the flow rate falls on the initial sections of the perforation, since its participation in this case is minimal.

Conclusion. Modeling of working sections of a wellbore (wellbores, perforation) by a set of nodes-spheres and the solution for system of analytical equations for each node taking into account their interference allows solving a number of problems:

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• replace a wide variety of analytical formulas describing a steady flow of fluid to different types of wells with different working sections of the wellbore(s);

• find solutions for those cases that cannot be described by analytical equations, or described with large assumptions;

• describe the inflow to the perforation, thereby increasing the accuracy of determining the skin effect or the RP parameter;

• choose the most effective system of well drainage taking into account features of a reservoir.

Performed modeling confirmed a number of known patterns:

• the highest density of fluid inflow is characteristic for final sections of a wellbore (wellbores, perforation);

• difference between the flow rates of HW and fracture of the same length increases with rising ratio of the formation thickness to the length of the wellbore;

• anisotropy coefficient, proportion of shot or drilled formation thickness, distance between perforation and others have a significant effect on the productive characteristics of the well during secondary drilling-in.

It is shown that the deteriorated properties of the formation at the initial drilling-in have almost no effect on the total skin effect determined by hydrodynamic investigations, because the main inflow falls on the end sections of the perforation.

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