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Modeling of non-stationary fluid inflow to a multisectional horizontal well

P.E. Morozov
Institute of Mechanics and Engineering, FRC Kazan Scientific Center of the Russian Academy of Sciences, Kazan, Russian Federation
E-mail: morozov@imm.knc.ru

Abstract. For a more uniform production of oil reserves, horizontal wells are equipped with intelligent completion systems with remotely controlled multisection inflow control equipment and sensors to monitor pressure and temperature. A new semi-analytical solution of the problem of non-stationary fluid inflow to a multisectional horizontal well in an anisotropic reservoir is obtained. Typical curves of the pressure and pressure derivative in the isolated sections of the horizontal wellbore are built, taking into account the skin factor and the effect of the wellbore volume. It is shown that, for isolated sections of the horizontal wellbore with the help of profile reservoir separators and packers, the pressure response in inactive sections occurs with a delay. At the same time, inactive sections have little effect on the pressure change in the active section. With the decrease in the length of the reservoir uncouplers, the mutual influence of the active and inactive sections is strengthened. The effect of the fluid "crossflow" through the inactive sections of the horizontal wellbore has been revealed. A similar effect of fluid "crossflow" is observed in the trunk of a horizontal well after its stopping, as well as in the intervals of penetration by the stopped imperfect vertical well.

Keywords: multisectional horizontal well, intelligent well, semi-analytical solution, non-stationary inflow, pressure curve, skin factor, fluid "crossflow" effect

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At present, in the development of oil and gas fields with hard-to-recover reserves, horizontal drilling technology is widely used. The main advantage of drilling horizontal wells (HW) is an increase in the drainage area due to the expansion of the contact area with the reservoir. The length of the trunk can reach several hundred meters, and in some cases several kilometers. To more evenly produce oil reserves in heterogeneous formations, the horizontal wells are equipped with intelligent completion systems with remotely controlled multisectional inflow control equipment and sensors to monitor the pressure and temperature in each section. Figure 1 shows one of the schemes for separating a horizontal well into a section with electrically controlled inflow control valves developed at Tatneft PJSC. To isolate the sections from one another, profile strippers of lengths of 15-20 m and expandable packers are used. Separation of a horizontal trunk into sections with the possibility of cutting off sections as they are watered increases the manageability of the mining and reduces operating costs (Takhautdinov et al., 2013; Abdrakhmanov et al., 2017; Sagidullin et al., 2017).

Due to the fact that intelligent horizontal wells are becoming more common, the current task is to develop a methodology for interpreting the results of hydrodynamic studies of such wells in order to determine the reservoir's filtration parameters and optimal operating conditions. Graphoanalytical methods for interpreting the results of hydrodynamic researches of HW are based on the analysis of diagnostic pressure and pressure derivative graphs from the logarithm of time. On the diagnostic charts, separate regimes of fluid flow to the HW trunk and the parameters of the reservoir and well are determined from the angle of inclination of the pressure-change curve in the corresponding coordinates: vertical and horizontal permeability of the reservoir, skin effect and effective length of the horizontal trunk. Often on diagnostic charts, the initial radial and linear modes of fluid flow to the HW are masked by the effect of the volume of the wellbore. The horizontal permeability of the reservoir is determined by the late pseudo-radial flow regime to the HW, the time of its development depends on the length of the wellbore and may be longer than the time of the well investigation.

In work (Frick et al., 1996) a method of hydrodynamic researches of HW in isolated segments was proposed, which makes it possible to determine the permeability and local skin factor in the tested intervals of the HW.

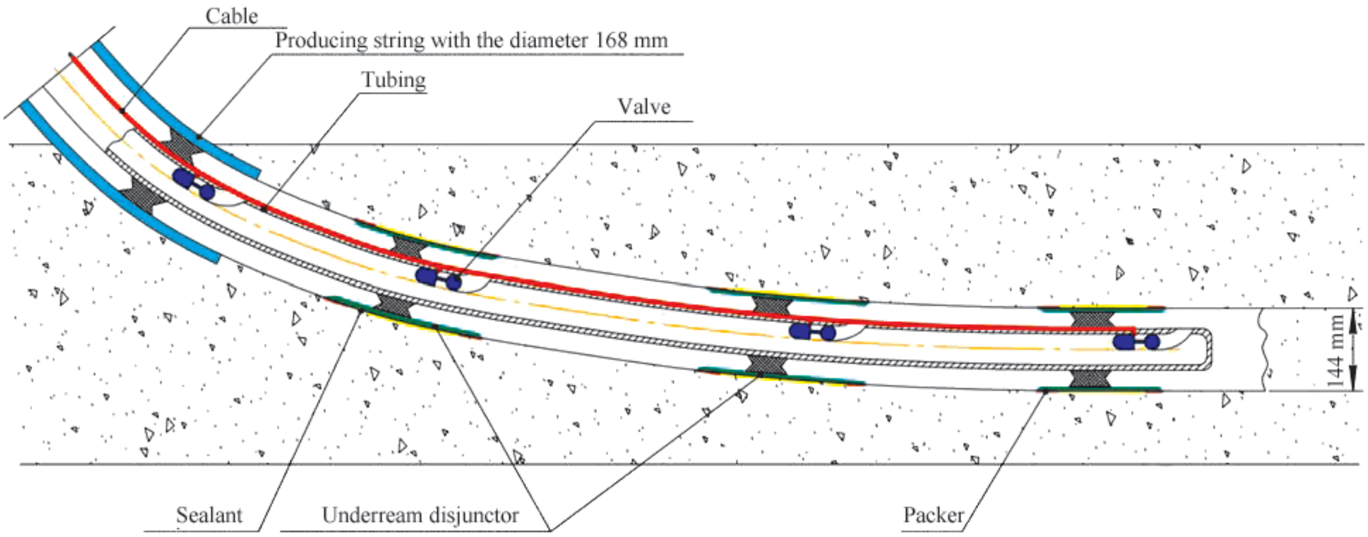


Figure 1. Scheme of multi-sectional HW with electrocontrolled flow control valves (Takhautdinov et al., 2013)

It is shown that from the pressure measurements in the HW segments isolated from the tested interval by means of packers, it is possible to obtain additional information on the permeability of the formation. Analytical solutions are presented in (Kamal et al., 1993; Yildiz et al., 1994; Rbeawi et al., 2014; Li et al., 2016; He et al., 2017) of the non-stationary inflow of liquid to a horizontal well with several production intervals. In the works (Kamal et al., 1993, Yildiz et al., 1994) it is noted that hydrodynamic research methods do not allow to obtain information on the number and length of inflow intervals to the HW, and geophysical methods should be used to extract them. In the works (Muslimov et al., 2003; Morozov et al., 2007) a technique is proposed for interpreting the pressure curves taken simultaneously at different sections of the horizontal wellbore.

In the present paper, a new semi-analytical solution is obtained for the problem of non-stationary fluid flow to a multisectional horizontal well. The principal difference of this solution from the known analytical solutions, for example, presented in the works (Kamal et al., 1993, Yildiz et al., 1994; He et al., 2017), is the account of the isolation of HW sections from each other with the help of seam breakers and packers. Another equally important difference is the consideration of the uniform pressure distribution in the sections of the HW. On the basis of the solution obtained, the effect of opening and closing the inflow control valves on the pressure and pressure derivative curves in isolated sections of the HW trunk is analyzed.

A semi-analytical solution of the problem

Let us assume that the anisotropic reservoir has an impenetrable roof and a bottom, and is unrestricted along its strike. We direct the x axis along the HW trunk, and the z axis vertically upwards (Figure 2).

Let the HW trunk be divided into N sections and a liquid with constant production rate Q be taken from the k-th section. We assume that the pressure distribution in each section of the HW trunk is uniform, i.e. (equation). To solve the problem, we use the solution for a point source in an anisotropic reservoir, bounded by two parallel impermeable planes (Ozkan et al., 1991). By integrating elementary sources with a flow density q along the sections of the HW, taking into account the assumption of a uniform pressure distribution on the cylindrical surfaces of sections, we obtain a system of integral equations for determining the Laplace image of the pressure functions $p_i(t)$ and the fluid flow distribution $q_i(x, t)$ along the length of the sections of the HW (Morozov, 2017):

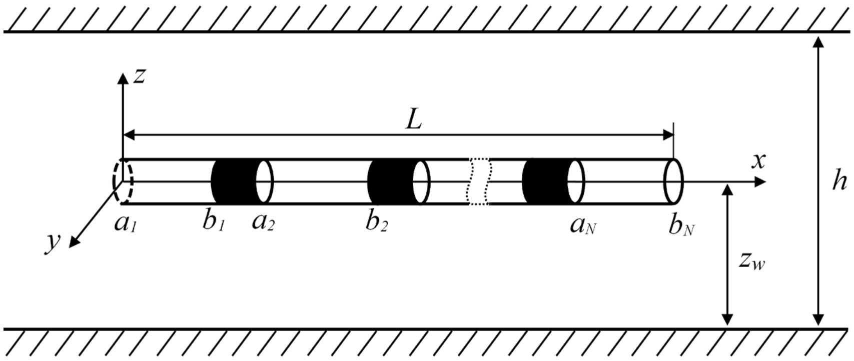


Figure 2. Scheme of the reservoir, penetrated by a multisectional horizontal well

$$\overline{p}_{id}(u) = S_i l_{di} \overline{q}_i(x_d, u) + \frac{1}{2}\sum_{j=1}^{N}\int_{a_{dj}}^{b_{dj}} \overline{q}_j(x_d, u)\Big[K_0\left(\sqrt{u}\left|x_d - x'\right|\right) +$$

$$+ 2\sum_{n=1}^{\infty} K_0\left(\sqrt{u + \xi_n^2}\left|x_d - x'\right|\right)\cos\xi_n z_{wd}\cos\xi_n\left(z_{wd} + r_{cd}\right)\Big]dx',$$

$$x_d \in \left(a_{di}, b_{di}\right),\ i = \overline{1, N} \qquad (1)$$

$$\int_{a_{di}}^{b_{di}} \overline{q}_i(x', u)dx' = \begin{cases} \dfrac{1}{u} - C_{id} u \overline{p}_{id}(u),\ i = k, \\ -C_{id} u \overline{p}_{id}(u),\ i \neq k. \end{cases} \qquad (2)$$

where u – the Laplace transform variable;

$p_{id} = \dfrac{2\pi k_h h\left(p_k - p_i(t)\right)}{\mu Q}$ – the non-dimensional pressure in the i-th section of the HW trunk; $l_{di} = b_{di} - a_{di} = (b_i - a_i)/L$ – the dimensionless length of the i-th section; p_k – the reservoir pressure; $t_d = \dfrac{k_h t}{\mu \beta^* L^2}$ – dimensionless time; k_v, k_h – vertical and horizontal permeability; β^* – the elastic capacity of the reservoir; μ – the viscosity; $C_{id} = \dfrac{C_i}{2\pi h \beta^* L^2}$ – dimensionless coefficient of influence of the volume of the i-th section of the HW trunk; S_i – skin factor of the i-th section;

$$x_d = \frac{x}{L};\quad \xi_n = \frac{\pi n}{h_d};\quad h_d = \sqrt{\frac{k_h}{k_v}}\frac{h}{L};$$

$$r_{cd} = \frac{r_c}{2L}\left(1 + \sqrt{\frac{k_h}{k_v}}\right);\quad z_{wd} = \sqrt{\frac{k_h}{k_v}}\frac{z_w}{L};$$

$K_0(z)$ – a modified Bessel function of the second kind of the 0-th order. The skin factor S_i characterizes the additional filtration resistance in the near wellbore zone of the i-th section of the HW trunk. Since the sections are isolated from one another, $C_i = \beta V_i$, where β is the fluid compressibility, V_i is the volume of the i-th section of the HW trunk.

We note that for N = 2, the system of integral equations (1) – (2) is also a solution of the problem of interference of active and observable horizontal wells of length l_1 and l_2, respectively, whose axes lie on one straight line. In contrast to the solutions of the analogous problem presented in the works (Malekzadeh et. al., 1991; Al-Khamis et. al., 2005; Awotunde et. al., 2008), decision (1) – (2) is taken into account skin factor and the effect of the volume of the trunks of active and observational horizontal wells.

In the event that liquid is withdrawn not from one section but simultaneously from several sections of the HW (the inflow control valves in these sections are open), we assume that the pressure in the respective sections is uniformly distributed. Let, for example, a liquid with a constant production rate Q be selected from sections of the HW with indices from the set I. Then, instead of (2), we write:

$$\sum_{i \in I}\int_{a_{di}}^{b_{di}} \overline{q}_i(x', u)dx' = \frac{1}{u} - C_d u \overline{p}_d(u),$$

$$\int_{a_{di}}^{b_{di}} \overline{q}_i(x', u)dx' = -C_{id} u \overline{p}_{id}(u),\ i \notin I, \qquad (3)$$

where $p_d = p_{id}$, $i \in I$ is the dimensionless pressure in the active sections of the HW trunk, C_d is the dimensionless coefficient of influence of the volume of the active sections of the HW trunk.

Let us suppose now that all inflow control valves are open and fluid is withdrawn from all sections of the HW with a constant production rate Q. We will assume that in this case the sections of the HW trunk are not isolated from each other and the pressure in the sections is evenly distributed. Then the system of integral equations (1), (3) is a solution of the problem of non-stationary fluid inflow to a horizontal well with several production intervals. A similar solution of the problem was obtained in a paper (Li et al., 2016), in contrast to the works (Kamal et al., 1993; Yildiz et al., 1994; He et al., 2017), where it was assumed that the inflow of liquid to the production intervals is uniformly distributed.

In case of dual operation of the multi-sectional HW, when the selection of fluid from each section is independent, equations (2) must be replaced by equations

$$\int_{a_{di}}^{b_{di}} \overline{q}_i(x', u)dx' = \frac{\alpha_i}{u} - C_{id} u \overline{p}_{id}(u),\ i = \overline{1, N}, \qquad (4)$$

where $\alpha_i = \dfrac{Q_i}{Q}$ – is the share of the i-th section in the total producton rate of multisectional HW $Q = \sum_{i=1}^{N}\left|Q_i\right|$, Q_i – the production rate of the i-th section, $\sum_{i=1}^{N}\left|\alpha_i\right| = 1.$

If we put N = 2 in the system of integral equations (1), (4), we obtain a solution to the problem of interference of two sections of the HW or two operational horizontal wells whose axes lie on the same straight line.

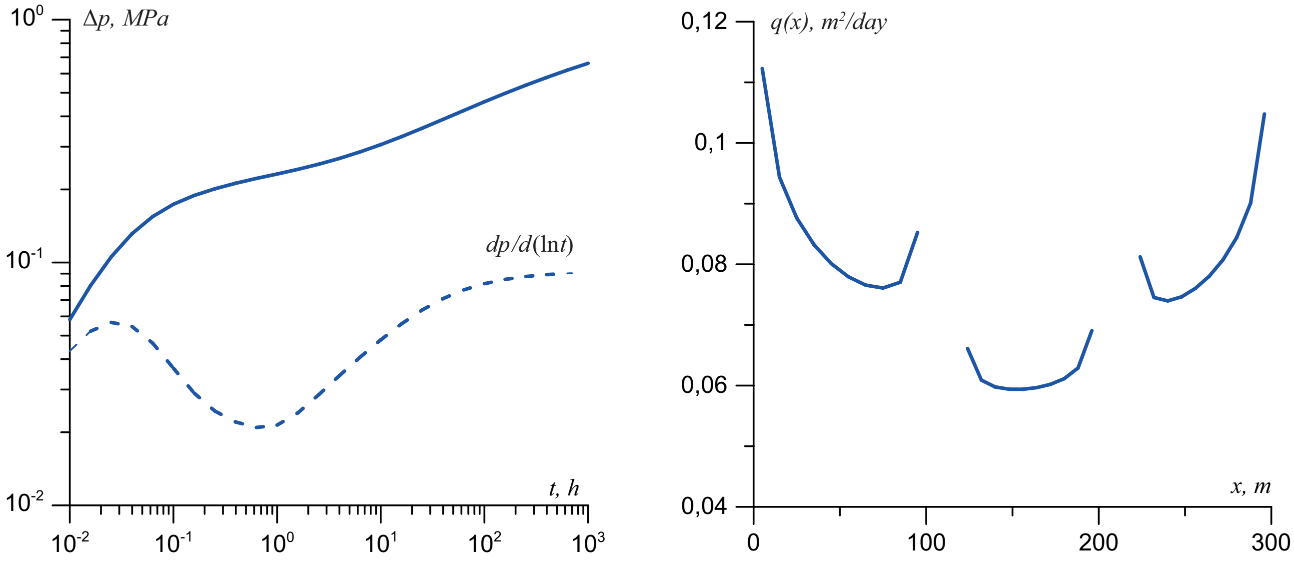
For the numerical solution of systems of integral equations (1) – (2), (1), (3) or (1), (4), each section of the HW trunk is divided into segments and it is assumed that the inflow of liquid to the segments is uniform. Substituting the coordinates of the segment centers instead of xd, we obtain a system of algebraic equations for determining the Laplace image of the functions of changing the pressure and fluid flow to the sections of the HW trunk. The originals of the inflow and pressure functions are numerically based on the Stefest algorithm, which requires a multiple solution of a system of linear algebraic equations with a dense matrix. To solve this problem, we use a stabilized method of BiCGStab bi-conjugate gradients with preconditioning.

Results of calculations

As an example, the problem of non-stationary fluid flow to a horizontal well in an anisotropic layer is considered, the trunk of which is divided into three sections. The calculations were carried out with the following initial data: L = 300 m, h = 20 m, z_w = 10 m, a_1 = 0 m, b_1 = 100 m, a_2 = 120 m, b_2 = 200 m, a_3 = 220 m, b_3 = 300 m, k_h = 0.1 μm², k_v = 0.01 μm², μ = 10 mPas, $\beta^* = 1 \cdot 10^{-4}$ MPa^{-1}, Q = 20 m³/day, C_1 = 0.1 m³/ MPa, C_2 = 0.01 m³/MPa, C_3 = 0.01 m³/MPa, S_1 = 0, S_2 = 1, S_3 = 0.5. With numerical realization of the problem solution, each section of the HW trunk was divided into 10 uniform segments.

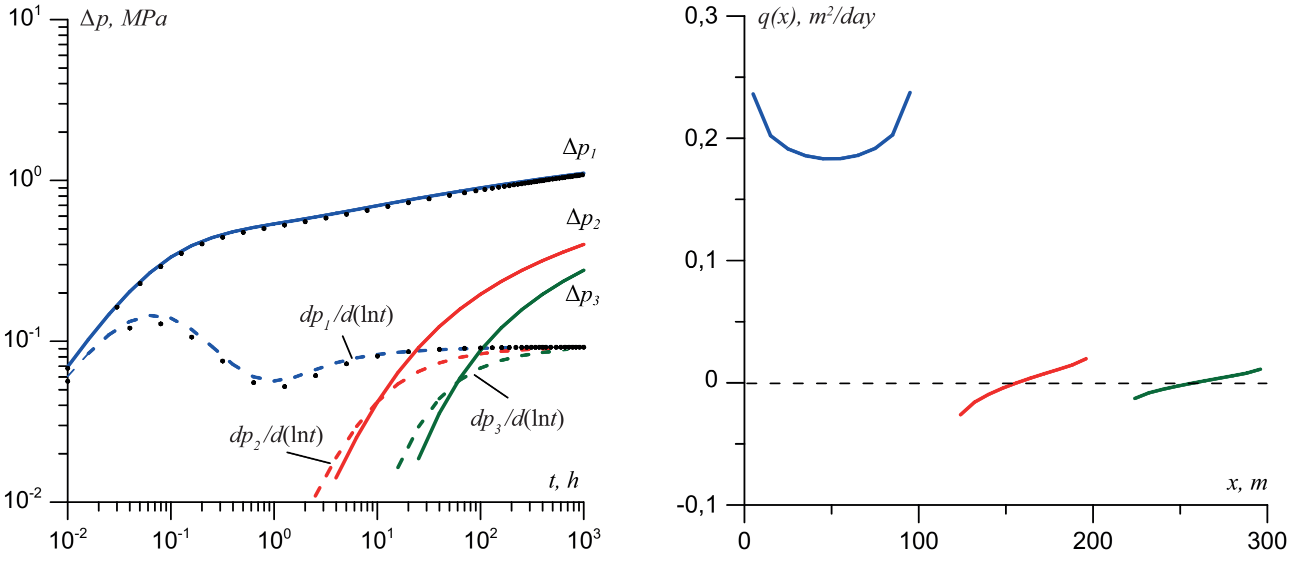
In the first example, it is assumed that a horizontal well is put into operation with a constant production rate Q when all inflow control valves are open. In this case, the pressure along the HW trunk is distributed uniformly ($p_1 = p_2 = p_3$), with the inflow of fluid moving along the entire trunk, except for the areas covered by the reservoir uncouplers. Figure 3a shows the pressure and pressure derivative curves in the HW, and Figure 3b – the distribution of fluid flow along the trunk of the HW at the final moment of time. The slight asymmetry of the fluid flow along the HW stem is due to the difference in the skin factor in the individual sections of the HW trunk.

In the following example, it is assumed that only the first inflow control valve is open. Figure 4a shows the pressure and pressure derivative curves in sections of the HW trunk. For comparison, Figure 4, and the symbols show the results of calculations of pressure and pressure derivative in a HW with a trunk length of 100 m, obtained in the "Saphir" package of KAPPA Engineering. An analysis of the pressure derivative in



a) b)

Figure 3. Pressure and pressure derivative curves (a) and distribution of fluid flow along the HW trunk (b), all valves are open



a) b)

Figure 4. Pressure and pressure derivative curves (a) and distribution of fluid flow along the HW trunk (b), the first valve is open

the active section of the HW trunk showed that, due to a decrease in the operating length of the HW, the time to reach the late radial flow regime is almost an order of magnitude lower than in the previous example. Since the sections are isolated from each other by profile breakers and packers, the pressure response in the inactive sections of the HW trunk occurs with a delay, and for the third section the pressure response time is the longest, and the amplitude of the pressure change is smaller. Inactive sections of the HW trunk have little effect on the pressure change in the active section. With the decrease in the length of the layer uncouplers, the mutual influence of the active and inactive sections will be strengthened.

Figure 4b shows a graph of the distribution of the liquid inflow to the sections of the HW at the final moment of time. It can be seen that fluid flow through the inactive sections of the HW trunk. This effect is explained by the fact that sections of the HW trunk are channels of “infinite conductivity” and a part of the liquid in the reservoir flows along the path of the least filtration resistance. Thus, inactive sections of the HW simultaneously inflow of liquid from the formation and outflow of liquid into the reservoir, and for large times the total inflow and outflow is zero. It should be noted that the effect of fluid “overflow” also occurs in the trunk of the observation horizontal well with interference from two horizontal wells (Malekzadeh et al., 1991; Al-Khamis et al., 2005; Awotunde et al., 2008). In addition, this effect is observed in the trunk of a horizontal well after its stop (Morozov, 2009), as well as in the intervals of opening of the stopped imperfect vertical well (Morozov, 2017).

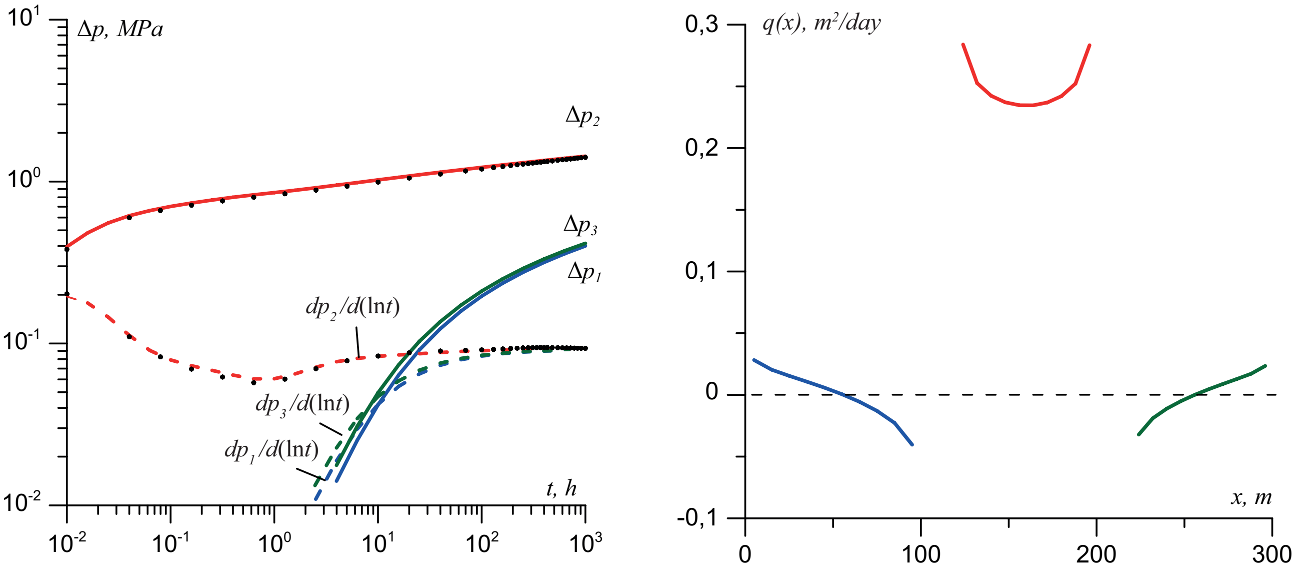
Figure 5a shows the pressure and pressure derivative curves in the HW sections in the case where the second inflow control valve is open. The time delay and the amplitude of the pressure response in the inactive sections of the HW trunk practically coincide. The symbols in Figure 5a shows the results of calculations of the pressure and pressure derivative in a HW with a barrel length of 80 m and a skin factor $S = 1$ obtained in the Saphir package. As in the previous example, a fluid flow occurs through inactive sections of the HW trunk (Figure 5b).

Figure 6a shows the pressure and pressure derivative curves in the sections of the HW in the case where the first and third inflow control valves are open ($p_1 = p_3$). On the graph of the pressure derivative in the active sections of the HW trunk, two sections can be distinguished, characterizing the pseudo-radial flow regime. The first section characterizes the pseudo-radial flow regime to the active sections of the HW trunk prior to their mutual influence, the second section is the pseudo-radial flow regime to the HW at large times.

Comparing the derivatives of pressure in Figure 3a and Figure 6a, it is seen that with the disconnection of the second section of the HW trunk, the time to reach the late radial flow regime changes insignificantly. The fluid flow through the second section, which is located between the active sections of the HW trunk, has an arcuate shape (Figure 6b). The slight asymmetry in the inflow of the liquid in Figure 6b is due to the difference in the skin factor in the trunk sections of the HW.

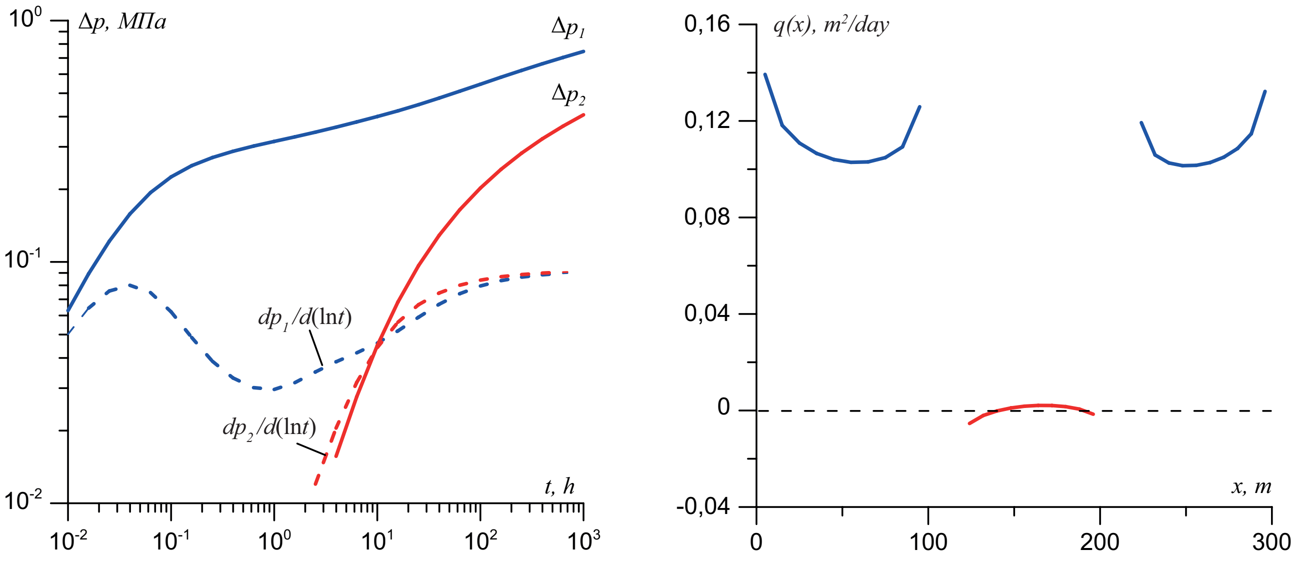
Conclusions

The paper provides a semi-analytical solution to the problem of non-stationary inflow of liquid to a multi-section horizontal well with controlled selection. The effect of the opening and closing of the inflow control valves on the pressure and pressure derivative curves



a) b)

Figure 5. Pressure and pressure derivative curves (a) and distribution of fluid flow along the HW trunk (b), the second valve is open



a) b)

Figure 6. Pressure and pressure derivative curves (a) and distribution of fluid flow along the HW trunk (b), the first and third valves are open

in sections of the HW trunk is analyzed. Calculations showed that through the inactive sections of the HS trunk an "overflow" of the liquid takes place. Therefore, the effect of the "overflow" of the liquid should be taken into account when conducting and interpreting the results of thermohydrodynamic studies of multi-section horizontal wells with controlled selection.

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About the Author

Petr E. Morozov – PhD (Engineering), Senior Researcher, Laboratory of Underground Hydrodynamics

Institute of Mechanics and Engineering, FRC Kazan Scientific Center of the Russian Academy of Sciences

2/31, Lobachevsky St., Kazan, 420111, Russian Federation

Tel: +7 (843) 292-93-45, e-mail: morozov@imm.knc.ru

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