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Modeling of oil filtration processes around horizontal wells in hard reaching anisotropic reservoirs

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SUMMARY

On the base of combined finite element - difference method, we carried out computer modeling of filtration processes around horizontal producing wells in anisotropic hard reaching oil reservoirs. According to obtained data analysis, for effective exploitation of anisotropic hard reaching oil reservoirs, it is necessary to install horizontal production wells in areas with relatively low anisotropy of the reservoir permeability, to avoid places with the presence of shear permeability of the oil reservoir. The most effective arrangement of horizontal producing wells in anisotropic reservoirs is their diagonal location relatively reservoir anisotropy axes. At the same time, it is necessary to carry out a systematic analysis of the surrounding anisotropy of the oil reservoirs in order to place a horizontal well in such a way that would provide an effective dynamics of filtration processes around the well. That is, on the one hand, there was no blocking of oil from the side of reduced permeability, another hand, there was no rapid depletion of the reservoir from the side of increased permeability, at that equable access of oil to the producing well from all possible directions was ensured.

Introduction

In our days, there are actual problems of effective supporting of the stable production in anisotropic hard to reach oil reservoirs. For that purposes in practice, different modern technologies of the oil filtration processes activity increasing around producing wells have been used (Mishenko, 2015), (Tuna, 2018). There are different technologies, which can influence on the main filtration parameters of the oil reservoir such as permeability, porosity, viscosity and other methods which allow hard to reach reservoirs exploitation. However, for effective using of such technologies in practice it is necessary to understand the complete picture of anisotropic filtration processes around production wells in anisotropic hard to reach oil reservoirs. In such situation, computer methods of the anisotropic heterogeneous oil reservoirs modeling are very effective, because they able to obtain information about anisotropic filtration processes near acting production wells in many practical cases. Furthermore, they allow evaluate and take into account some specific details which impossible to get outside of wells. Moreover, we can obtain such information by comparatively cheap way. Nowadays, there are many effective methods of the oil reservoirs modeling, which allow resolving of various practical problems (Aziz and Settary, 2004), (Chen et. al., 2006), (Ertekin et. al., 2001). Another hand now remains the number of problems connected with accuracy and adequacy of specific anisotropic heterogeneous hard to reach oil reservoir systems modeling. Presented in this work combined computer method consisting of variation finite element method and method of finite differences (Lubkov and Zaharchuk, 2019) allows setting and calculation of the different filtration parameters in anisotropic heterogeneous oil reservoirs and also oil penetration conditions on the border of investigating area. Therefore, we can adequately calculate the distribution of the oil pressure around horizontal production wells in anisotropic heterogeneous hard to reach oil reservoir systems in realistic exploitation conditions.

Mathematical formulation and solving problem

We consider anisotropic oil reservoirs in which presence of the gas phase very small comparatively with oil phase. Suggesting, that thickness of the oil reservoir considerably lesser than its horizontal sizes, we can use two-dimensional anisotropic nonstationary piezoconductivity model. At that case, the ordinary formulation of piezoconductivity problem with calculation of oil penetration conditions in the borders of considering area in rectangular axes (X, Y) has view (Lubkov and Zaharchuk, 2019):

$$\frac{\partial P}{\partial t} = \frac{1}{c}\left(k_{xx}\frac{\partial^2 P}{\partial x^2} + k_{yy}\frac{\partial^2 P}{\partial y^2} + 2k_{xy}\frac{\partial P}{\partial x}\frac{\partial P}{\partial y}\right) + \gamma; \qquad (1)$$

$$P(t=0) = P_0; \qquad (2)$$

$$k\,\mathrm{grad}P = \alpha(P - P_b). \qquad (3)$$

Here (1) - anisotropic nonstationary piezoconductivity equation; (2) – initial condition; (3) – condition of oil penetration in the border of investigating area; $P(x,y,t)$ – pressure, as function of coordinates and time; $c = \eta(m\beta_1 + \beta_2)$ - coefficient of piezoresistivity; k_{xx}, k_{yy}, k_{xy}- anisotropic coefficients of the oil permeability; η – dynamic oil viscosity; m – porosity reservoir coefficient; β_1- compressibility of the oil phase; β_2- compressibility of skeleton of the porous rocks; P_0 – initial pressure of the oil reservoir; P_b – pressure in the border of investigating reservoir; α - coefficient of oil penetration in the border; γ - oil production parameter.

For resolving the anisotropic nonstationary piezoconductivity problem, we use variation finite element method, which leads to the solving of variation piezoconductivity equation:

$$\delta\,\mathrm{I}(P) = 0. \qquad (4)$$

Here I(P) – functional of anisotropic piezoconductivity problem (1) – (3), which has a view (Lubkov and Zaharchuk, 2019):

$$\mathrm{I}(P) = \frac{1}{2}\iint_S \left\{k_{xx}\left(\frac{\partial P}{\partial x}\right)^2 + k_{yy}\left(\frac{\partial P}{\partial y}\right)^2 + 2k_{xy}\frac{\partial P}{\partial x}\frac{\partial P}{\partial y} + 2\int_{P_0}^{P} c\frac{\partial P}{\partial t}dP - 2\gamma P\right\}dxdy - \frac{1}{2}\int_L \alpha(P - 2P_b)P\,dl \qquad (5)$$

here, S – the square of investigating reservoir; L – contour, which surrounds the square S, dl – element of the contour.
For resolving variation equation (4), we use eight-nodal isoparametric quadrangular finite element (Lubkov and Zaharchuk, 2019). As global coordinate system, where we unit all finite elements of investigating area S, rectangular system (X, Y) is used. As local coordinate system, where in limits of every finite element we define approximation functions φ_i and make numerical integration, normalizing coordinate system (ξ, η) is used. In this system coordinates, pressure, initial pressure, pressure in the border of investigating area, coefficient of the oil penetration in the border and derivatives of pressure on coordinates approximated in such way:

$$x=\sum_{i=1}^{8}x_i\varphi_i;y=\sum_{i=1}^{8}y_i\varphi_i;P=\sum_{i=1}^{8}P_i\varphi_i;P_0=\sum_{i=1}^{8}P_{0i}\varphi_i;P_c=\sum_{i=1}^{8}P_{ci}\varphi_i;\alpha=\sum_{i=1}^{8}\alpha_i\varphi_i;$$

$$\frac{\partial P}{\partial x}=\sum_{i=1}^{8}P_i\Psi_i;\frac{\partial P}{\partial y}=\sum_{i=1}^{8}P_i\Phi_i;\Psi_i=\frac{1}{|\mathrm{J}|}\left(\frac{\partial\varphi_i}{\partial\eta}\frac{\partial y}{\partial\xi}-\frac{\partial\varphi_i}{\partial\xi}\frac{\partial y}{\partial\eta}\right);\Phi_i=\frac{1}{|\mathrm{J}|}\left(\frac{\partial\varphi_i}{\partial\xi}\frac{\partial x}{\partial\eta}-\frac{\partial\varphi_i}{\partial\eta}\frac{\partial x}{\partial\xi}\right);\tag{6}$$

the $\mathrm{J}=\frac{\partial y}{\partial\xi}\frac{\partial x}{\partial\eta}-\frac{\partial y}{\partial\eta}\frac{\partial x}{\partial\xi}$ - Jacobian matrix between systems (x, y) and (ξ,η).
Following variation equation (4) and suggesting, that nodal meanings from derivatives of pressure on time $\frac{dP_i}{dt}$ are known values and aren't variated, we get system of differential equations for k – nodal of p – finite element in such view;

$$\frac{\partial \mathrm{I}_p}{\partial P_k}=\sum_{i=1}^{8}\{\mathrm{H}_{ki}^p\frac{dP_i}{dt}+(A_{ki}^p+\mathrm{Q}_{ki}^p)P_i-\mathrm{Q}_{ki}^p P_0^i\}-\gamma_k^p=0;\tag{7}$$

$$\mathrm{H}_{ij}^p=\int_{-1}^{1}\int_{-1}^{1}c^p\varphi_i\varphi_j|\mathrm{J}|d\xi d\eta;\mathrm{A}_{ij}^p=\int_{-1}^{1}\int_{-1}^{1}(k_{xx}^p\Psi_i\Psi_j+k_{yy}^p\Phi_i\Phi_j+k_{xy}^p\Psi_i\Phi_j)|\mathrm{J}|d\xi d\eta;\mathrm{Q}_{ij}^p=\int_L\alpha\varphi_i\varphi_j dl;$$

$$\gamma_i^p=\int_{-1}^{1}\int_{-1}^{1}\gamma^p\varphi_i|\mathrm{J}|d\xi d\eta.$$

For resolving the system of linear differential equations of the first order (7) at initial conditions (6) we use method of finite differences. At that, approximation of derivative in time we can realize on the base of implicit differential scheme (Aziz and Settary, 2004):

$$\frac{dP}{dt}=\frac{P(t+\Delta t)-P(t)}{\Delta t}.\tag{8}$$

Putting expression (8) into the system (7), we obtain the next system of linear algebraic equations:

$$\sum_{i=1}^{8}\{(\frac{1}{\Delta t}\mathrm{H}_{ki}^p+A_{ki}^p+\mathrm{Q}_{ki}^p)P_i(t+\Delta t)-\frac{1}{\Delta t}\mathrm{H}_{ki}^p P_i(t)-\mathrm{Q}_{ki}^p P_0^i\}-\gamma_k^p=0\ (k=1-8).\tag{9}$$

After summing equations (9) by all finite elements, we obtain the global system of linear algebraic equations, which allows defining unknown meanings of pressure in the moment of time $t+\Delta t$ via their meanings at previous moment t. We resolve the global system equations on the base of Gauss numerical method (Lubkov and Zaharchuk, 2019). After solving, we can define the pressure at all nods of the finite element net. Therefore, we can determine reservoir oil pressure in any points of investigating reservoir in any time.

Modeling of filtration processes near horizontal oil production wells in anisotropic reservoirs
Let's consider anisotropic oil reservoir area in vicinity of producing horizontal wells with the length of 90 m. In modeling, we suggest the initial reservoir pressure of 20 MPa and average power of oil production wells is 100 m^3 over day. We choose some typical parameters of the oil reservoir (Basniev et al., 2003): η = 10^{-3} Pa·s; m = 0,2; β_1 = 10^{-9} Pa^{-1}; β_2 = 10^{-10} Pa^{-1}, at that case coefficient of piezoreistivity c = 0,3·10^{-12} s. For the edge area effects minimizing, we suggest oil penetration coefficients on the borders of considering area equaled 0,001 m. We have illustrated the obtained

results of anisotropic oil filtration processes near horizontal production wells modeling by the figures 1- 4:

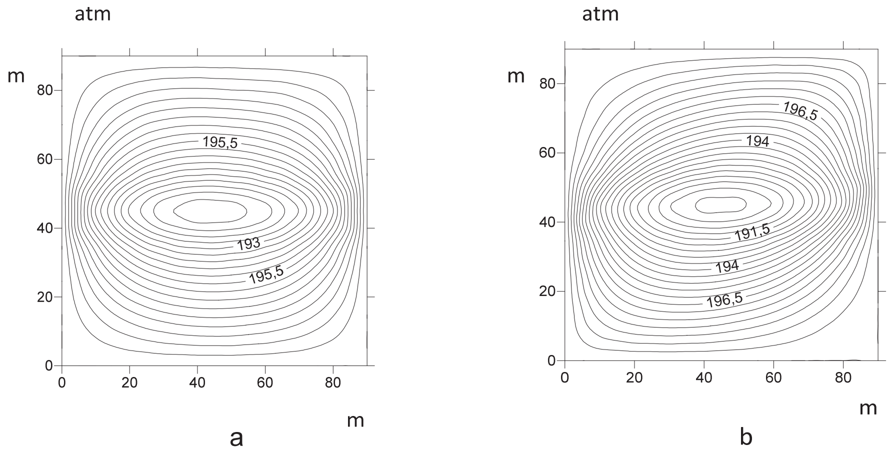

Figure 1. a, b *Distribution of stable pressure in vicinity of horizontal well (directed along X axe) in absolute and shifting isotropic cases: a)* $k_{xx} = k_{yy} = 1D$*,* $k_{xy} = 0$*; b)* $k_{xx} = k_{yy} = k_{xy} = 1D$ *(Darsi)* $= 10^{-12}$ m^2*.*

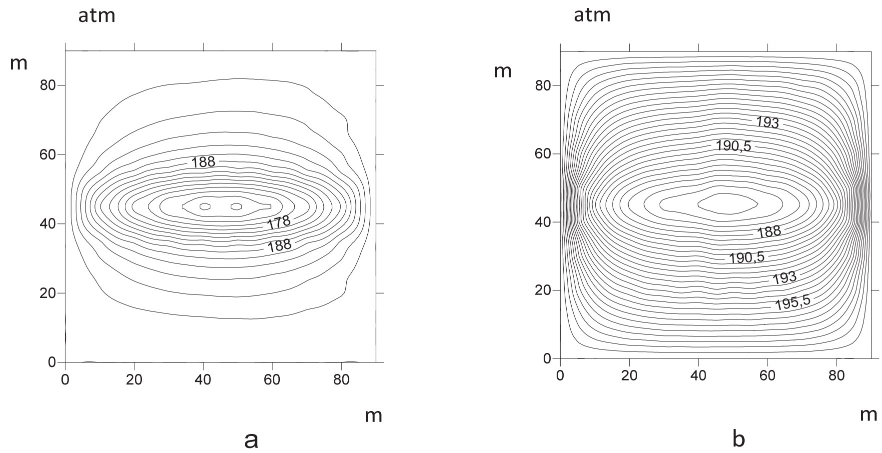

Figure 2. a, b *Distribution of stable pressure in vicinity of horizontal well (directed along X axe) at different anisotropic permeability parameters of the oil reservoir: a)* $k_{xx} = 1D$*,* $k_{yy} = 0,1D$*,* $k_{xy} = 0$*; b)* $k_{xx} = 0,1D$*,* $k_{yy} = 1D$*,* $k_{xy} = 0$*.*

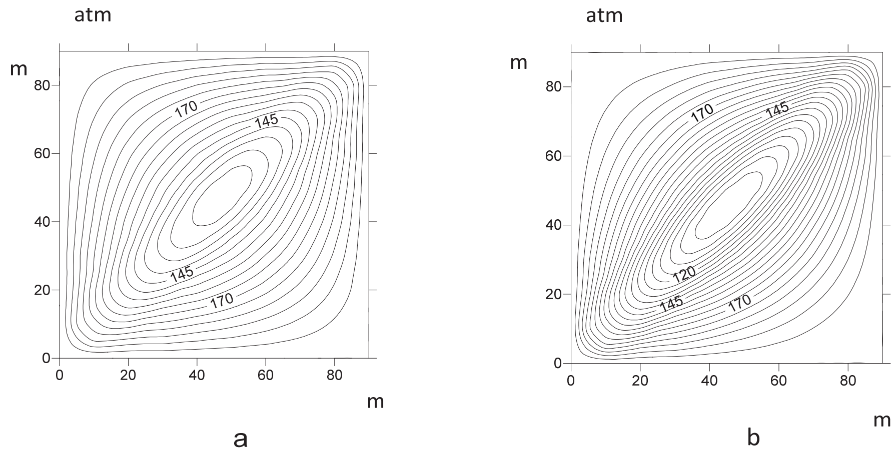

Figure 3. a, b *Distribution of stable pressure around horizontal well (directed along diagonal direction of reservoir anisotropy) in absolute and shifting isotropic cases: a)* $k_{xx} = k_{yy} = 0,1D$*,* $k_{xy} = 0$*; b)* $k_{xx} = k_{yy} = k_{xy} = 0,1D$*.*

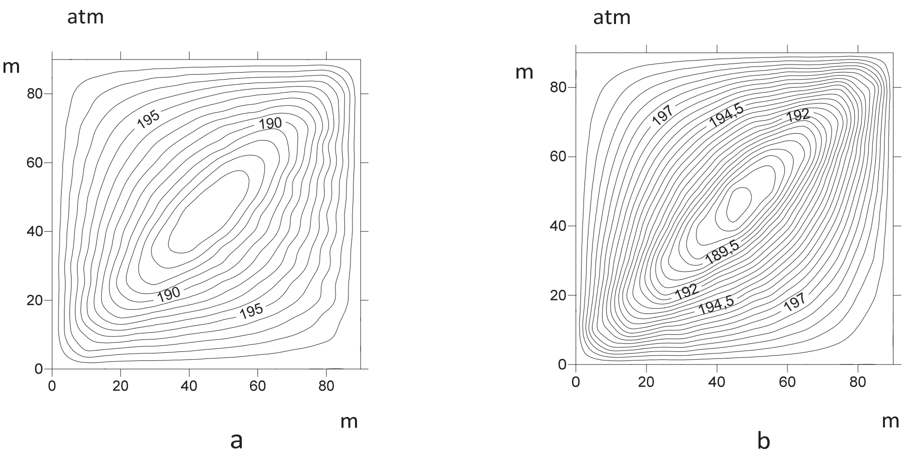

Figure 4. a, b *Distribution of stable pressure around horizontal well (directed along diagonal direction of reservoir anisotropy) at different anisotropic permeability parameters of the oil reservoir: a)* $k_{xx} = 1D$*,* $k_{yy} = 0{,}1D$*,* $k_{xy} = 0$*; b)* $k_{xx} = 0{,}1D$*,* $k_{yy} = 1D$*,* $k_{xy} = 0$*.*

Conclusions

The elaborated combined finite element - differences method of resolving anisotropic nonstationary piezoconductivity problem in deforming oil reservoirs allows adequately in the quantity level describing of the filtration processes around horizontal oil producing wells in hard reaching realistic exploitation conditions. The obtained results show that the intensity of the filtration process around the horizontal well significantly depends on its location in the anisotropic oil reservoir. We have obtained, for effective using of anisotropic hard-to-reach oil reservoirs, it is necessary to place horizontal production wells in areas with relatively low anisotropy of reservoir permeability, especially to avoid places with shear permeability of the oil reservoir. The most effective installation of horizontal production wells in the oil anisotropic reservoirs is its diagonal arrangement relatively the reservoir anisotropy axes. It is necessary to carry out a systematic analysis of the surrounding anisotropy of the oil reservoirs in order such horizontal well placement, which would provide intensive dynamics of filtration processes around the well. On the one hand should not be blocking of oil from the side of reduced permeability, and another hand should not be rapid depletion of the reservoir from the side of increased permeability and must be free access of oil to the production well from all possible directions. Obviously, for achievement the best conditions of the horizontal oil production in any practical case we have to optimally calculate all important factors of the oil anisotropic reservoir exploitation. Another hand, we can evaluate these factors by using of presented method.

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