The Influence of Discontinuities on Waterflooding process

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Abstract: - The knowledge of the nature of fluid motion in the reservoir allows us to optimize a system of oilfield development. Thus, the study of filtration process in reservoirs with discontinuities, such as fractures, has a great importance for the oilfield development. For instance, the hydraulic fracturing is one of the most common recovery methods for unconventional reserves. The modern level of geophysics can show that most reservoirs have the tectonic faults of different permeability which have a great impact on well productivity. This article will show the impact of inclusions of different permeability in the reservoir on the waterflooding process. The steady-state flow process of incompressible fluid to the production well in a reservoir of constant height and permeability is considered. There is a thin area in the reservoir with constant permeability, which might be a highly permeable crack or low permeable barrier. The production and injection wells are placed inside the reservoir's external boundary. The characteristics of waterflooding process are studied for various permeability values and different locations of a fracture and a pair of wells. Finally, the flow lines of the fluid flow will be analyzed for every considered case.

Key-Words: - waterflooding, hydraulic fracturing, Darcy flow, impermeable boundary, flow potential, streamlines.

1 Introduction

Waterflooding is the earliest and the most widely used secondary oil recovery technique. It is known that more than a half of oil in the world [1] and more than 90% of oil in Russia [2] is produced with water injection. The main reasons of wide application of this method are low cost of water, simplicity of the process and high effectiveness [3]. The importance of waterfooding causes the actuality of study the geophysical factors of the process and modeling of oil displacement.

One of the first printed works devoted to the waterfooding is the Muskat's book [4], where the author studied the theoretical fundaments for simple models, such as radial and linear flow, and for more complex, such as the filtration process from the production to injection wells. The last problem is well known as "Musket's problem", and it is widely used for the analysis of more complicated methods. In addition to the mathematical models of flow processes there are a lot of physical experiments, for example in the work [3] the results of tests are presented with use of electrical and potential models, shape photography and X-rays.

Nowadays the most part of oil and gas reserves is located in low permeable formations, which requires new more complicated ways of extraction. Profitable production of hydrocarbons usually needs application of massive hydraulic fracturing technique [4]. So it becomes necessary to predict the performance of hydraulically fractured wells and evaluate the effectiveness of production system, taking into account fracture length and orientation [5].

Mostly the numerical simulation is used for the prediction of complicated fluid flow [4], but commonly these methods are time consuming. The main part of published papers about the waterflooding well-placement is dedicated to one special case. So we need to develop a new more faster and more exact semi-analytical technique to estimate the productivity of a well and even the most suitable well pattern, taking fractures into account.

This article discusses the fluid flow to a single production well in a reservoir with fractures of different permeability and shows the impact of such inclusions in a reservoir on the waterflooding process. The production and injection wells are mostly placed as some periodic array of wells [7]. This pattern may be considered as element of unbounded double periodic array of wells [8].

The prediction of shape and motion of the boundary between two fluids has a great importance for efficiency estimation [8]. The simplest two-phase filtration model is the model, which assumes that oil and water have similar physical properties. A more complicated “piston like” model takes into account the differences in viscosity and density of oil and injected water [8-13].

Firstly, the analytical model for a simple case with single production well is discussed. The influence of impermeable boundary or permeable fracture is taken into account. Secondly, the problem is solved for a pair of wells. This solution takes into account all cases of the well and the fracture locations and all values of fracture permeability. The steady-state flow process of incompressible fluid to the production well is considered. There is a thin area in the reservoir with constant permeability, k_f, which might be a highly permeable crack or low permeable barrier. The production and injection wells are placed inside the reservoir’s external boundary. The task is modified by the representation of crack in the section view of zero thickness but finite conductivity and by the difference of pressure above and below the section. In the last part of this paper, the method of calculation of water breakthrough time is defined and analyzed depending on the change in the input parameters. In the final part of the paper, the flow lines of the fluid flow are analyzed for every considered case.

2 Problem Formulation

We consider a plane stationary flow of incompressible fluid to the vertical production well in an isotropic porous medium. Filtration process is described by the Darcy's law and by the equation of incompressibility:

$$div\vec{V}(x,y)=0, \qquad \vec{V}=-(k/\mu)grad\ p, \qquad (1)$$

where $\vec{V}(x,y)$ is the velocity vector of fluid filtration, μ is the fluid viscosity, $p(x,y)$ is the pressure in the liquid, k is the reservoir permeability and h is the thickness of the reservoir.

Let us consider, that in plane (x,y) in the reservoir with the external boundary of radius R_c at the point $M_1(x_1,y_2)$ is placed the production well of radius r_w with a flow rate Q and at the point $M_2(x_1, y_1)$ is placed the injection well of the same radius. Inside the external boundary there is a crack with length $2l$ and thickness 2δ $(\delta << l)$ and permeability k_f. Let us consider that the crack is oriented along the axis x, and its center coincides with the origin plane (0, 0) (Fig. 1).

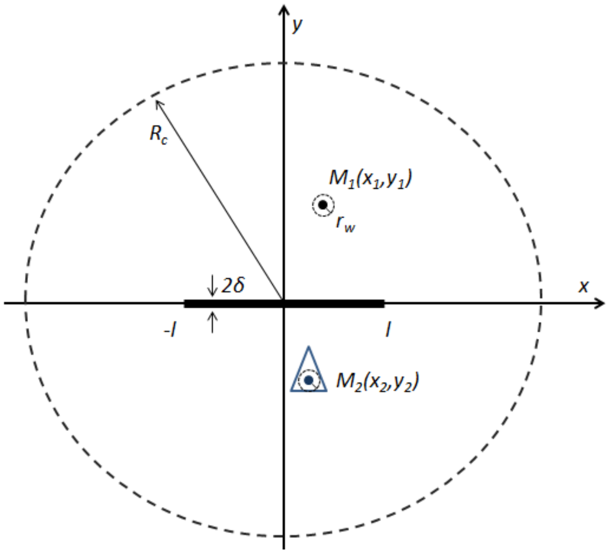

Figure 1 *Production and injection wells and fracture places in the plane.*

2.1 Model for a single well

To find the field of velocities, it is necessary to define the flow potential. Then, as described in work written by Astafiev and Fedorchenko [14], the flow potential for the radial flow to the single production well, can be represented in the next form:

$$\Phi(z)=q^{-1}\varphi(z)=\ln(z-z_0)+\sum_{n=0}^{\infty}c_n z^{-n}. \qquad (2)$$

where $q=\mu Q/(2\pi kh)$ is the modified flow rate, c_n is unknown coefficients in the expansion in a Laurent series of the disturbance caused by the presence of reservoir heterogeneity and decaying at infinity.

Many authors, for example Prats [15] and Kanevskaya [16, 17] solved this problem for the hydraulic fracturing or symmetrical case, when the well is located on the fracture line. In that case we need the parameter *Fcd*, dimensionless fracture conductivity, as the fluid just flows into the fracture and then the flow to the well occurs inside the fracture. But if we consider nonsymmetrical case, when the well is located at some distance from the fracture, or we have a couple of injection and production wells, we need to evaluate the inflow and the outflow from the fracture. In the paper, published earlier by Astafiev and Fedorchenko [14], the problem was solved with the assumption that the pressure is the same on the upper and lower banks of the crack. Now we consider the case with the difference of pressure above and below the section, and we use more complicated boundary conditions [18-22]:

$$\begin{cases} \alpha_0\sqrt{1-\xi^2}\,\dfrac{d}{d\xi}\mathrm{Re}(\Phi^+ + \Phi^-) = \mathrm{Im}(\Phi^+ - \Phi^-), \\ \beta_0\sqrt{1-\xi^2}\,\dfrac{d}{d\xi}\mathrm{Im}(\Phi^+ + \Phi^-) = -\mathrm{Re}(\Phi^+ - \Phi^-); \end{cases} \quad (3)$$

where Φ^+ and Φ^- are the flow potentials above and below the section, coefficient $a_0=\delta k_f/lk$ is similar to *Fcd* for the hydraulic fractures and $\beta_0=\delta k/lk_f$ is very important for the impermeable case.

In the papers, published by Astafiev and Andriyanova [18, 19, 22], the flow potential was expressed by the next equation:

$$\Phi(\nu) = \ln(\nu-\nu_0) + C + \sum_{n=1}^{\infty}\left[\frac{n\cdot\alpha_0-1}{n\cdot\alpha_0+1}\frac{\cos n\theta_0}{n\rho_0^n} - i\frac{n\cdot\beta_0-1}{n\cdot\beta_0+1}\frac{\sin n\theta_0}{n\rho_0^n}\right]\nu^{-n}, \quad (4)$$

where ν is a new variable after the mapping by the Zhukovsky function $z=l(\nu+\nu^{-1})/2$, $z=x+iy$ and it is equal to $\nu = \xi + i\eta = \rho e^{i\theta}$, $\nu_0 = \rho_0 e^{i\theta_0}$.

In case when $\theta_0=0$ or $\theta_0=\pi$, in other words, if the well is located on the x axis, this solution coincides with the solution obtained in the work written by Astafiev and Fedorchenko [14]:

$$\Phi(\nu) = \ln(\nu-\nu_0) + \sum_{n=1}^{\infty}\frac{1}{n}\left[\frac{n\cdot F_{cd}-1}{n\cdot F_{cd}+1}\left(\nu\overline{\nu_0}\right)^{-n}\right] + C_0.$$

2.1 Model for a pair of wells

Considering the case when we have a pair of wells, the flow potential can be expressed by the next equation:

$$\varphi(z) = q_1\ln(z-z_1) + q_2\ln(z-z_2) + \sum_{n=0}^{\infty}c_n z^{-n}. \quad (5)$$

If we map by the Zhukovsky function $z=l(\nu+\nu^{-1})/2$ and consider the case when $q_1=1$ and $q_2=-1$ or injection and production wells, flow potential can be written as follows:

$$\varphi(\nu) = \ln\frac{(\nu-\nu_1)}{(\nu-\nu_2)} + \sum_{n=1}^{\infty}a_n\nu^{-n} + C_0, \quad (6)$$

where variables $\nu_1 = \rho_1\cdot e^{i\theta_1}$, $\nu_2 = \rho_2\cdot e^{i\theta_2}$ and $a_n = a_n^{(s)} + ia_n^{(\alpha)}$.

The unknown coefficients $a_n^{(\alpha)}$ and $a_n^{(\beta)}$ can be found from the boundary conditions (3) as follows:

$$a_n^{(s)} = \frac{n\cdot\alpha_0-1}{n\cdot\alpha_0+1}\frac{\left(\dfrac{\cos n\theta_1}{\rho_1{}^n} - \dfrac{\cos n\theta_2}{\rho_2{}^n}\right)}{n};$$
$$a_n^{(\beta)} = -\frac{n\cdot\beta_0-1}{n\cdot\beta_0+1}\frac{\left(\dfrac{\sin n\theta_1}{\rho_1{}^n} - \dfrac{\sin n\theta_2}{\rho_2{}^n}\right)}{n}. \quad (7)$$

So, if we insert (7) into (6), the flow potential can be expressed by the following form:

$$\varphi(\nu) = \ln\frac{(\nu-\nu_1)}{(\nu-\nu_2)} + \sum_{n=1}^{\infty}\left[\frac{n\cdot\alpha_0-1}{n\cdot\alpha_0+1}\left(\frac{\cos n\theta_1}{n\rho_1{}^n} - \frac{\cos n\theta_2}{n\rho_2{}^n}\right) - i\frac{n\cdot\beta_0-1}{n\cdot\beta_0+1}\left(\frac{\sin n\theta_1}{n\rho_1{}^n} - \frac{\sin n\theta_2}{n\rho_2{}^n}\right)\right]\nu^{-n} + C. \quad (8)$$

If we consider that wells are located at the y axis, symmetrically from the fracture, or $\rho_1=\rho_2=\rho_0$ $\theta_1=\pi/2;\theta_2=-\pi/2$, $\nu_1=i\rho_0$; $\nu_2=-i\rho_0$;, then:

$$\varphi(\nu) = \ln\frac{(\nu-i\rho_0)}{(\nu+i\rho_0)} + \sum_{n=1}^{\infty}\left[\frac{n\cdot\alpha_0-1}{n\cdot\alpha_0+1}\left(\frac{\cos n\pi/2}{n\rho_0{}^n} - \frac{\cos n\pi/2}{n\rho_0{}^n}\right) - i\frac{n\cdot\beta_0-1}{n\cdot\beta_0+1}\left(\frac{\sin n\pi/2}{n\rho_0{}^n} - \frac{\sin n\pi/2}{n\rho_0{}^n}\right)\right]\nu^{-n} =$$
$$= \begin{cases} \ln\dfrac{(\nu-i\rho_0)}{(\nu+i\rho_0)} + 2i\displaystyle\sum_{k=0}^{\aleph}\frac{(-1)^k}{(2k+1)\rho_0{}^{2k+1}}\nu^{-(2k+1)}; & \beta_0 = 0, \\ \ln\dfrac{(\nu-i\rho_0)}{(\nu+i\rho_0)} - 2i\displaystyle\sum_{k=0}^{\aleph}\frac{(-1)^k}{(2k+1)\rho_0{}^{2k+1}}\nu^{-(2k+1)}; & \beta_0 = \infty. \end{cases}$$

The results show us that the case when wells are located on the y axis, symmetrically from the fracture and the fracture is highly permeable coincides with the Muskat's problem [7].

$$\varphi(\nu) = \ln\frac{\nu_1}{\nu_2} + \sum_{n=1}^{\infty}\left[\left(\frac{\cos n\theta_1}{n\rho_1^{\ n}} - \frac{\cos n\theta_2}{n\rho_2^{\ n}}\right)\left(\frac{n\cdot\alpha_0 - 1}{n\cdot\alpha_0 + 1}\nu^{-n} - \nu^n\right) - \right.$$
$$\left. - i\left(\frac{\sin n\theta_1}{n\rho_1^{\ n}} - \frac{\sin n\theta_2}{n\rho_2^{\ n}}\right)\left(\frac{n\cdot\beta_0 - 1}{n\cdot\beta_0 + 1}\nu^{-n} - \nu^n\right)\right].$$

For the case when $\alpha_0 = \infty$ and $\beta_0 = 0$, flow lines are shown in Fig. 2 (upper) and the flow potential can be expressed as follows:

$$\varphi(\nu) = \ln\frac{(\nu-\nu_1)}{(\nu-\nu_2)} - \sum_{n=1}^{\infty}\frac{1}{n}\left(\left(\nu\overline{\nu_1}\right)^{-n} - \left(\nu\overline{\nu_2}\right)^{-n}\right) = = \ln\frac{(\nu-\nu_1)}{(\nu-\nu_2)}\frac{\left(1-(\nu\overline{\nu_2})^{-1}\right)}{\left(1-(\nu\overline{\nu_1})^{-1}\right)}. \quad (9)$$

For $\alpha_0 = 0$ and $\beta_0 = \infty$, (Fig. 2, lower) the flow potential is equal to the Muskat's problem [7] and it can be expressed as follows:

$$\varphi(\nu) = \ln\frac{(\nu-\nu_1)}{(\nu-\nu_2)} + \sum_{n=1}^{\infty}\frac{1}{n}\left(\left(\nu\overline{\nu_1}\right)^{-n} - \left(\nu\overline{\nu_2}\right)^{-n}\right) = = \ln\frac{(\nu-\nu_1)}{(\nu-\nu_2)}\frac{\left(1-(\nu\overline{\nu_1})^{-1}\right)}{\left(1-(\nu\overline{\nu_2})^{-1}\right)}. \quad (10)$$

So for any cases, when the pair of wells is located symmetrically from the discontinuity for permeable fracture, the flow lines are similar to the flow without a fracture [7].

3 Flow lines and numerical calculations of waterflooding parameters

For the analysis of the oil-water boundary located between production and injection wells it is necessary to solve the following differential equation in complex variables [8]:

$$m\frac{d\bar{z}}{dt} = \overline{V}(z,\bar{z}) = \frac{k}{\mu}\frac{d\varphi(\nu)}{d\nu}\frac{d\nu}{dz} = \quad (11)$$
$$= \frac{Q}{2\pi h}\left(\frac{\nu_1}{\nu-\nu_1} - \frac{\nu_2}{\nu-\nu_2} \pm \sum_{n=1}^{\infty}\left(\left(\nu\overline{\nu_1}\right)^{-n} - \left(\nu\overline{\nu_2}\right)^{-n}\right)\right)\frac{1}{\sqrt{z^2-l^2}},$$

where m is the porosity of the reservoir, "+" before the sum relates to the case $\alpha_0 = \infty$ and $\beta_0 = 0$, and "-" relates to the case $\alpha_0 = 0$ and $\beta_0 = \infty$.

The initial condition at the time $t=0$ is:

$$z(\theta,0) = z_2 + r_w e^{i\theta} \quad (12)$$

where z_2 is the center of the injection well, r_w is the radius.

If we have two different liquids in the system, we face a new type of problems, when we have two areas filled with water and filled with oil. So both moving liquids need their own flow potential. Pressure and normal component of velocity should be continuous at the boundary between fluids, but flow potentials can be different [4]. To simplify this difference in our calculations we consider that the viscosity and density of fluids are the same. For the solution of the equation (11) with initial condition (12) we use the Runge-Kutta methods [8].

In the Fig. 2-7 we can see the results of calculations for several cases of wells and fracture locations for permeable and impermeable discontinuity. Different colors in these pictures show the boundaries between the flooding stages, so we can predict the water front at any moment, and water breakthrough time (the first colored zone, counting from the injection well, is the waterflooded area, from the beginning of the process to the half of the process; the second zone in the pictures is the waterflooded area, from the ½ of the process to the ¾ of the process; the third zone – the waterflooded area, from the ¾ of the process to the water breakthrough time; the last colored zone or the closest to the production well is the waterflooded area at the breakthrough time).To sum up the nature of fluid flow to a wellbore at different locations of the crack and the well for different values of the coefficients α_0 and β_0 are shown in Fig. 2-7. As we can see, the obtained flow potential equation allows us to solve the problem for any wells and fracture locations and for different fracture conductivity. In the upper figures there is the permeable fracture ($\alpha_0=\infty$; $\beta_0=0$) and if we place the well in the center of the fracture, we can see the hydraulic fracturing case. In the lower figures there is the impermeable fracture ($\alpha_0=0$; $\beta_0=\infty$), which acts like an impermeable boundary.

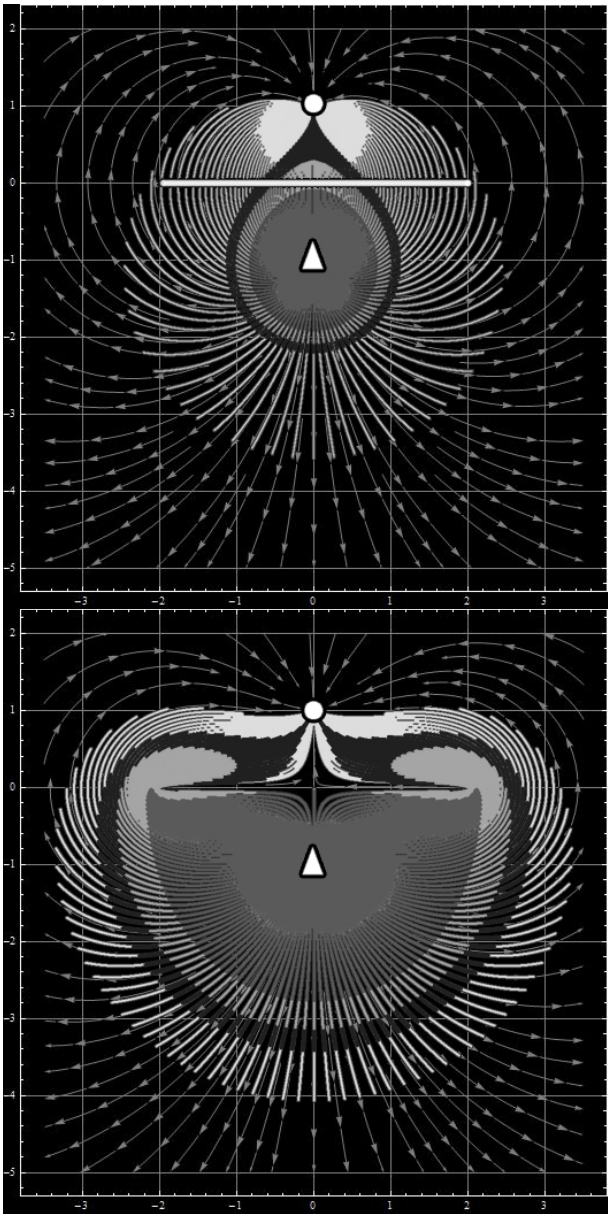

Figure 2 *Streamlines of a waterflooding process. The injection well is located at the point (0,-1), the production well is located at the point (0, 1); for the values of* $\alpha_0=\infty$*;* $\beta_0=0$ *(upper) and* $\alpha_0=0$*;* $\beta_0=\infty$ *(lower).*

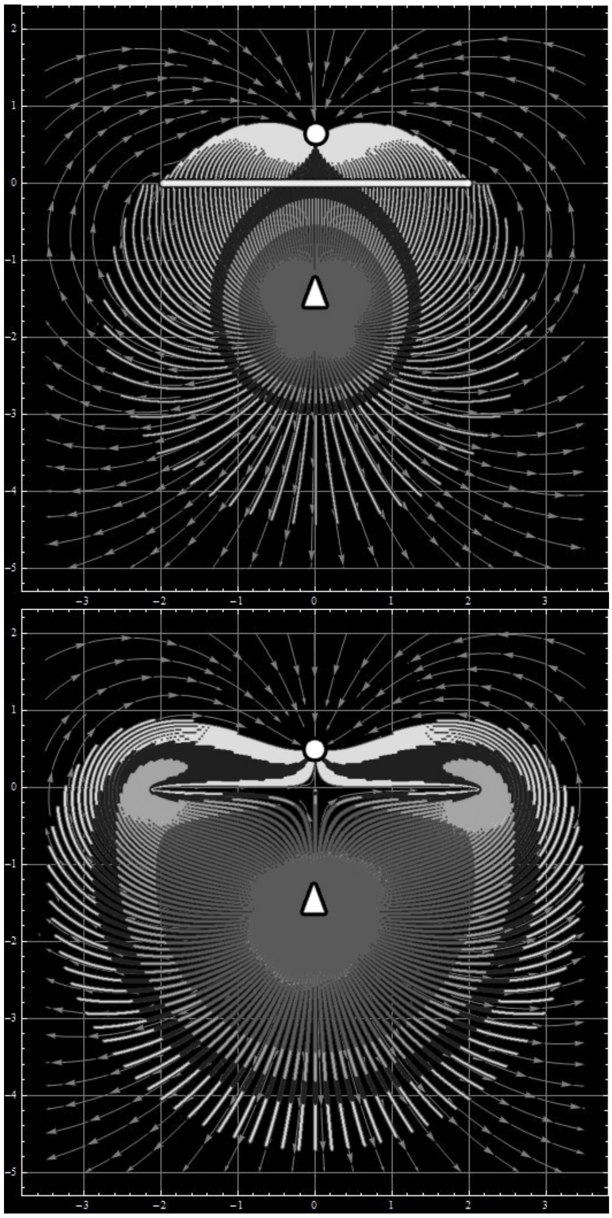

Figure 3 *Streamlines of a waterflooding process. The injection well is located at the point (0, -1.5), the production well is located at the point (0, 0.5); for the values of* $\alpha_0=\infty$*;* $\beta_0=0$ *(upper) and* $\alpha_0=0$*;* $\beta_0=\infty$ *(lower).*

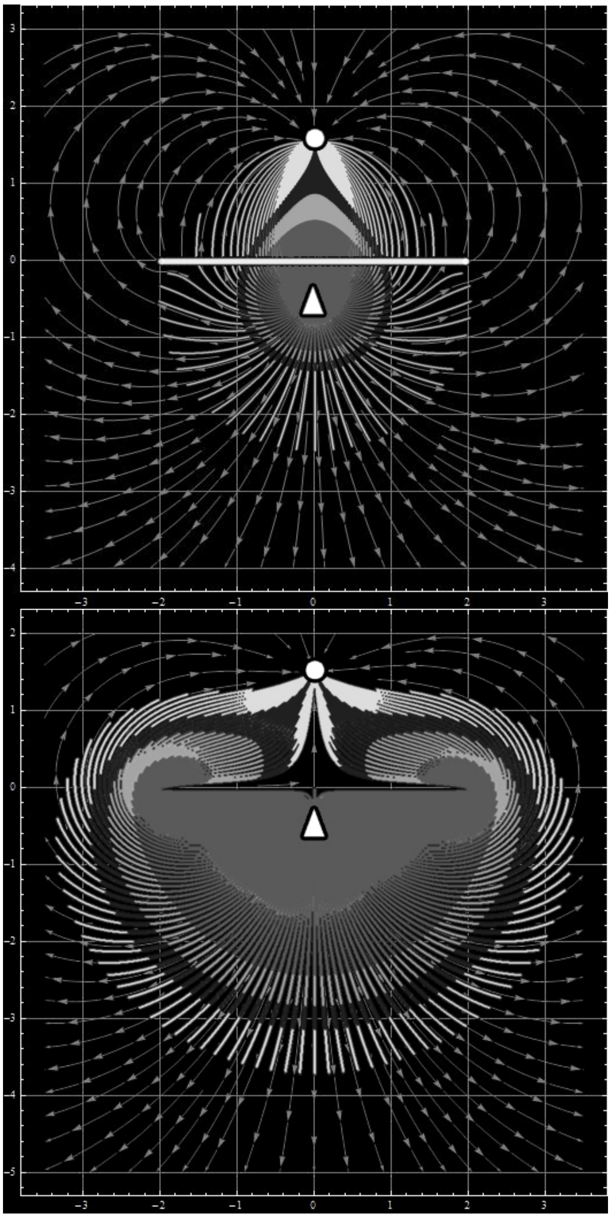

Figure 4 *Streamlines of a waterflooding process. The injection well is located at the point (0, -0.5), the production well is located at the point (0, 1.5); for the values of* $\alpha_0=\infty$; $\beta_0=0$ *(upper) and* $\alpha_0=0$; $\beta_0=\infty$ *(lower).*

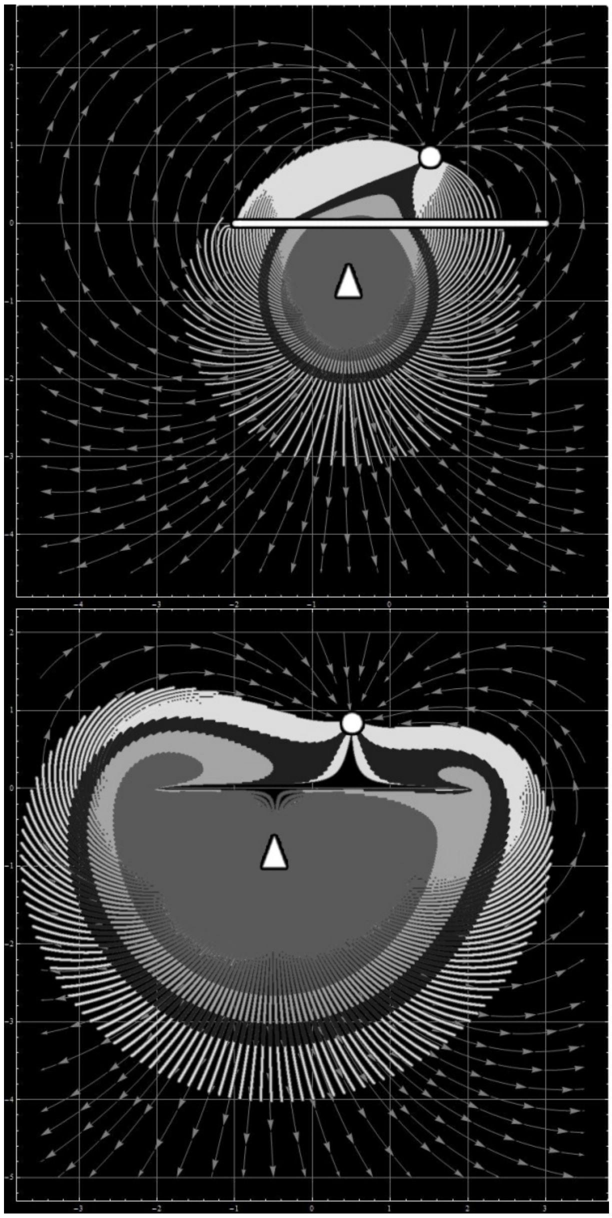

Figure 5 *Streamlines of a waterflooding process. The injection well is located at the point (-0.5, -1), the production well is located at the point (0.5, 1); for the values of* $\alpha_0=\infty$; $\beta_0=0$ *(upper) and* $\alpha_0=0$; $\beta_0=\infty$ *(lower).*

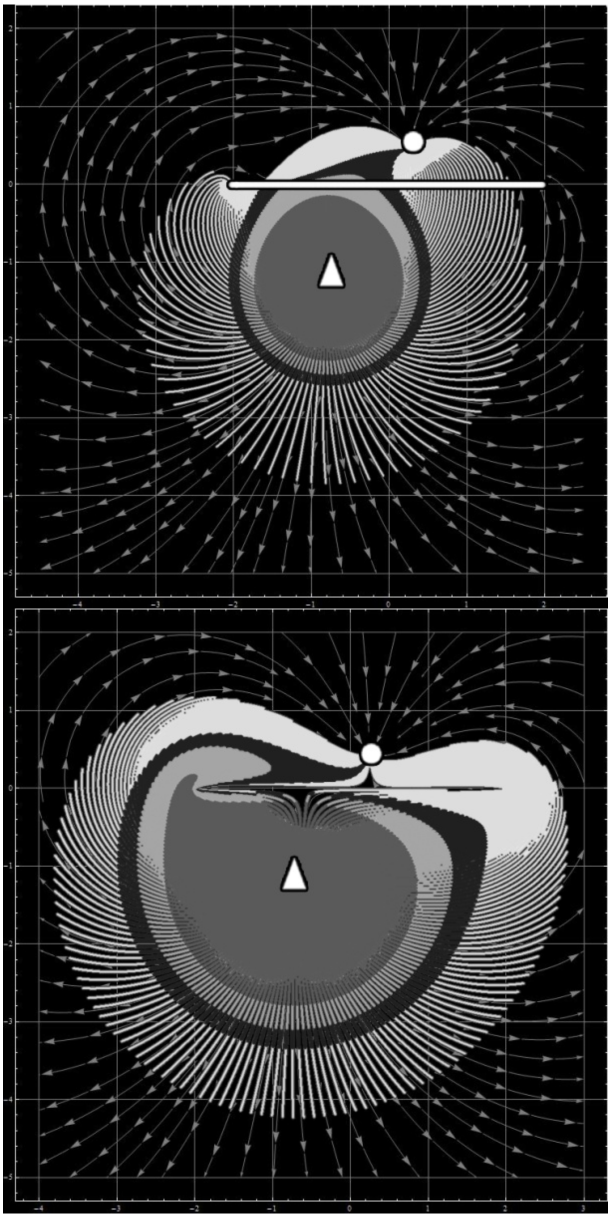

Figure 6 *Streamlines of a waterflooding a process. The injection well is located at the point (-0.5, -1.5), the production well is located at the point (0.5, 0.5); for the values of* $\alpha_0=\infty$; $\beta_0=0$ *(upper) and* $\alpha_0=0$; $\beta_0=\infty$ *(lower).*

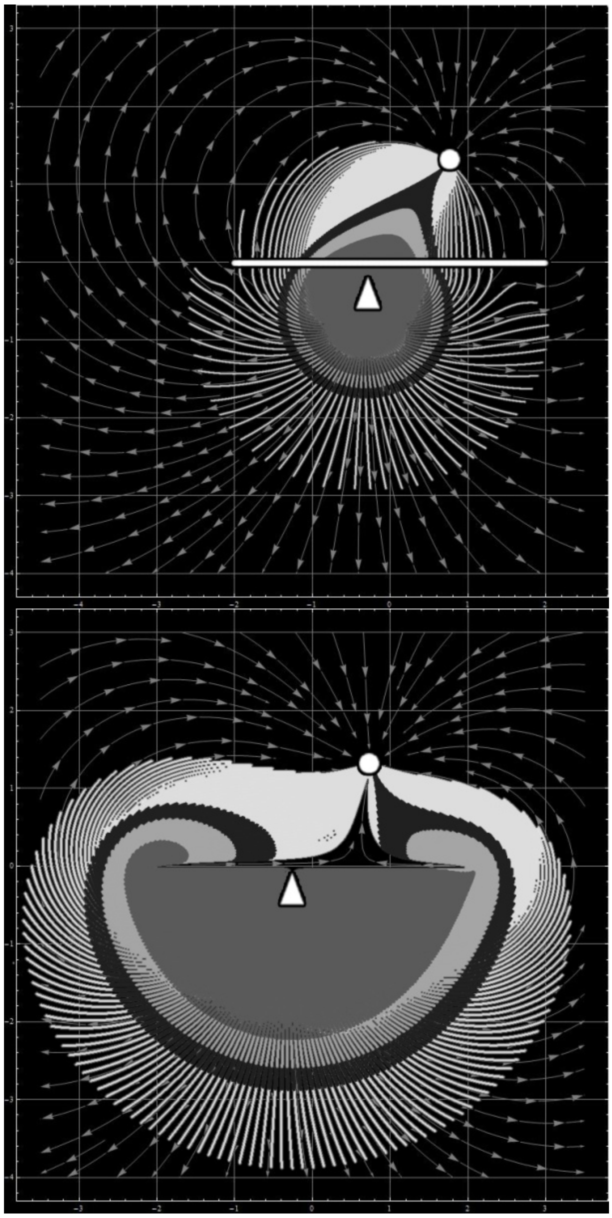

Figure 7 *Streamlines of a waterflooding process. The injection well is located at the point (-0.25, -0.25), the production well is located at the point (0.75, 1.25); for the values of* $\alpha_0=\infty$; $\beta_0=0$ *(upper) and* $\alpha_0=0$; $\beta_0=\infty$ *(lower).*

4 Conclusion

In this work the mathematical model of waterflooding process at the presence of a fracture of different permeability has been done. The solution obtained by the replacement of ellipse like approximation to the section view of zero thickness but finite conductivity. The more general boundary conditions were considered taking into account the pressure difference above and below the section.

Thus the more general equation was obtained for the flow potential which coincides with previous solutions. This solution is suitable for any cases of various well and fracture places and for different values of fracture permeability.

In the final part of the paper the nature of fluid flow was analyzed. It was concluded that for a case when wells are located symmetrically from the fracture, the permeable fracture does not influence on the flow. The streamlines of the waterflooding process were calculated. The method of calculation of the position of water front and water breakthrough time was received.

The problem has enough interest from the petroleum engineers. Further development of the solution is to present the flow potential through singular integral equations, which will greatly expand the applications.

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