Journal of Contemporary Applied Mathematics
V. 12, No 1, 2022, July
ISSN 2222-5498

Simulation of the Inference of Filter Operation Process on Oil and Gas Production Indicators

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Abstract. A model of influence of filters operation on oil production indicators was constructed with taking into account anisotropy and heterogeneity of the formation. Sand accumulation time was determined depending on the parameters of the system a formation a well and a filter. An analytic formula that allows to determine the criterion for the effectiveness of filters, the use was obtained.

Key Words and Phrases: integral simulation, filtration equation, inhomogeneous formation, permeable wall, anisotropy

1. Introduction

One of the methods of sand control is installation of filters on the well bottom [1-15]. The presence of filters reduces the formation sand entry into the well. This improves the permeability of oil and gas production equipments and prevents formation failure. However, at the same time, the presence of filters increases the hydranlical resistance and leads to accumulation of sand carried out by the flow from the formation in bottom hole zone of the well. This reduces the flow of liquid and gas per unit time from the formation to the well and in some cases in heavily sandy wells can lead to its complete extinction. The means to prevent sand production should ensure not only the retention of sand entering the wellbore, but also the stability of production over the entire life of the well [7]. Therefore, determining the influence of filters on the oil and gas production indicators is of great scientific and practical importance.

The works [2,3,6,7,12,13,17, 20-26] were devoted to study of influence of filters on oil and gas production.

For example, [7] analyzes the causes of sand entry, the methods for their prevention and the means used for this, and the balance between the cost- effectiveness of the use of filters and technological possibilities. The resulting benefit must be compared with the operating costs [7]. The loss of efficiency of sand control systems is being considered. We establish that filters can lose functionality due to unforeseen sand production or deviation of their sizes from the proposed ones [7].

The works [20-22] consider the influence of installation of wire filters to prevent sand production in the well operation process.

However, in these works, the mutual influences of the motion of liquid or gas in a porous medium through the filter walls and in the pipe string are not taken into account. This may lead to gross mistakes and wrong conclusions.

The influence of a filter on gas and oil production indicators taking into account the connection of the system a formation a well remains poorly understood to date and requires a comprehensive research.

In the present paper, we construct an integral model of the filtration process and motion of fluid in the pipeline at the presence of a filter at the well, and its influence on oil and determined gas production.

The initial stage of the filters work

After installation of the filter , sand fractions that can not pass through its opening, will gather around the filter and from a low permeability zone.

We consider the influence of this zone on oil filtration process. Constant pressure R_k is maintained on the external boundary of radius P_k, constant pressure P_c on the well bottom of radius r_c. We denote the radius of the boundary of the contour of zones by R_1, the pressure on this contour by P (Fig.1).

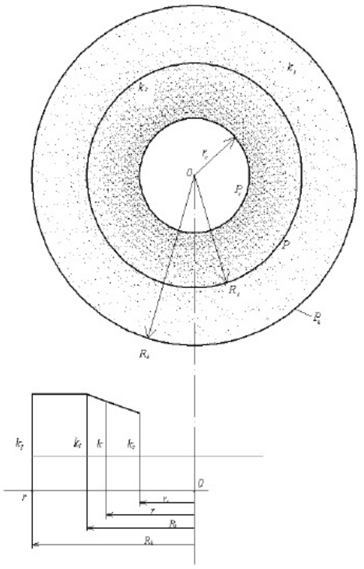

Fig 1. Calculation scheme.

In the case of a steady plane-radial motion of homogeneous fluid velocities V_1 and V_2 in the first and second zones of the system can be determined from the formulas [16]

$$V_1 = \frac{k_1}{\mu_n r} \frac{P_k - P}{\ln \frac{R_k}{R_1}} \tag{1}$$

$$V_2 = \frac{k_2}{\mu_n r} \frac{P - P_c}{\ln \frac{R_1}{r_c}} \tag{2}$$

The condition of flow continuity on the interface

$$V_1|_{r=R_1} = V_2|_{r=R_1} \tag{3}$$

Substituting expressions (1) and (2) in condition (3), we obtain

$$P = \frac{k_1 P_k \ln \frac{R_1}{r_c} + k_2 P_c \ln \frac{R_k}{r_c}}{k_1 \ln \frac{R_1}{r_c} + k_2 \ln \frac{R_k}{R_1}} \tag{4}$$

Fluid inflow per unit time into the well can be determined by the formula [16,17]

$$Q = \frac{2\pi k_2 h\,(P - P_c)}{\mu_n \ln \frac{R_1}{r_c}} \tag{5}$$

Substituting the expression (4) in formula (5), we obtain

$$Q = \frac{2\pi k_1 h\,(P_k - P_c)}{\mu_n \left(\frac{k_1}{k_2} \ln \frac{R_1}{r_c} + \ln \frac{R_k}{R_1}\right)} \tag{6}$$

In the absence of a filter, the fluid inflow into the well per unit time is determined by the formula [16].

$$Q_1 = \frac{2\pi k_1 h\,(P_k - P_c)}{\mu_n \ln \frac{R_k}{r_c}} \tag{7}$$

To assess the effect of the presence of a filter on the fluid inflow into the well per unit time, consider the ratio Q to Q_1.

$$Q_0 = \frac{Q}{Q_1} \tag{8}$$

By formula (8), a numerical calculation was carried out for the following values of the parameters:

$$R_1 = 5 \div 80m; k_0 = \frac{k_1}{k_2} = 1 \div 10; P_k = 5 \cdot 10^6 Pa;$$

$$\mu_n = 10^{-3} Pac; R_k = 100m;\ r_c = 7,5 \cdot 10^{-2} m; h = 30m.$$

The results of calculation are in Fig. 2.

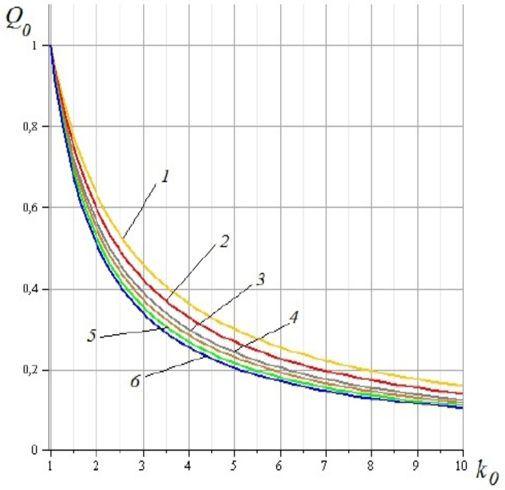

Fig.2. The graph of dependence of the ratio of debit in the presence of a filter to a debit without a filter on the ratio of permeability coefficients of the zones at different values of $R_1 : 1 - R_1 = 5m$;$2 - R_1 = 10m$; $3 - R_1 = 20m$;$4 - R_1 = 30m$; $5 - R_1 = 50m$; $6 - R_1 = 80m$.

As can be seen from Fig. 2, increasing the radius of the zone dividing contour the inflow into the well per unit time decreases. Furthermore decreasing in the permeability around the well zone, at first the inflow drops sharply, and then its decline rate degradates.

2. Accounting for inhomogeneity

Let us consider the heterogeneity in permeability in the radial direction in sand accumulation zone. In the first approximation, we accept that the change in permeability occurs according to a linear law. We assume that in the contact contour of the homogeneous and inhomogeneous zones, their permeability coefficients are the same. Sand compacts as it approaches the wellbore, and permeability factor decreases (Fig. 1). Then the permeability factor will be of the form:

$$k(r) = k_2 + \frac{k_1 - k_2}{R_1 - r_c} \cdot (r - r_c)$$

This time, the equation of flat-radial stationary filtration in the variable permeability zone will be of the form [16,17].

$$\frac{1}{r}\frac{d}{dr}\left[\frac{k(r)}{\mu\beta} r \frac{dP_2}{dr}\right] = 0 \tag{9}$$

The boundary conditions:

$$P_2\left|_{r=r_c} = P_c\right. \tag{10}$$

$$P_2\left|_{r=R_1} = P\right. \tag{11}$$

$$k_2 \, \frac{\partial P_2}{\partial r}\bigg|_{r=R_1} = k_1 \frac{\partial P_1}{\partial r} \,|_{r=R_1} \tag{12}$$

where P_1 is the pressure distribution in the first homogeneous zone, P_2 in the second inhomogeneous zone, P is the pressure at the interface between the first and second zones.

Integrating expression (9), taking into account the boundary conditions (10), (11) and (12), we obtain:

$$P_2 = \frac{(P_c - P)}{\ln \frac{k_1 r_c}{k_2 R_1}} \ln \left(\frac{r}{1 + \frac{k_1 - k_2}{k_2 R_1 - k_1 r_c} r} \right) + P_c - \frac{(P_c - P)}{\ln \frac{k_1 r_c}{k_2 R_1}} \ln \frac{r_c \, (k_2 R_1 - k_1 r_c)}{k_2 \, (R_1 - r_c)} \tag{13}$$

$$P = \frac{P_k \frac{k_0}{\ln \frac{R_k}{R_1}} - P_c \frac{R_1 - k_0 r_c}{k_0 (R_1 - r_c) \, \ln\left(k_0 \frac{r_c}{R_1}\right)}}{\frac{k_0}{\ln \frac{R_k}{R_1}} - \frac{R_1 - k_0 r_c}{k_0 (R_1 - r_c) \, \ln\left(k_0 \frac{r_c}{R_1}\right)}} \tag{14}$$

Fluid inflow into the well per unit time can be determined by the formula

$$Q = \frac{k_2}{\mu} 2 \, \pi \, r_c \, h \, \frac{\partial P_2}{\partial r}\bigg|_{r=r_c} \tag{15}$$

From equation (15), taking into account expressions (13), (14), we obtain

$$Q = 2 \, \pi \, h \, \frac{k_2}{\mu} \, \frac{P_c - P}{\ln\left(k_0 \frac{r_c}{R_1}\right)} \left(\frac{R_1 - k_0 \, r_c}{R_1 - r_c} \right) \tag{16}$$

Substituting the expression (16) in formula (8), we obtain a formula by which the numerical calculation is carried out for the following parameters for various values of permeability ratios $k_0 = \frac{k_1}{k_2}$.

The calculation results are in Fig. 3.

As can be seen from Fig.3, when the permeability around the well bottom is inhomogeneous, by increas in the radius of the contour dividing the zones, inflow into the well per unit time also decreases. However, the decline rate compared with the zonal inhomogeneous formation slows. Reducing permeability around the well zone, at first the inflow sharply, decreases and then its decline rate decreases.

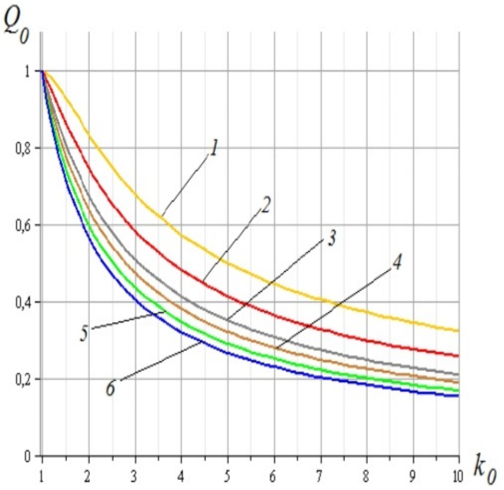

Fig.3. The graph of dependence of the ratio of debit in the presence of a filter to a debit without a filter on the ratio of permeability coefficients of zones in the case of inhomonogenity of the second zones of the farmation in the radial direction at different values $R_1 : 1 - R_1 = 5m$; $2 - R_1 = 10m$; $3 - R_1 = 20m$; $4 - R_1 = 30m$; $5 - R_1 = 50m$; $6 - R_1 = 80m$.

3. Accounting for anisotropy

Let now consider the case when the permeability of the second zone of the formation varies in vertical direction as well. This happens because of gravity of sand particles. In the lower part of the filter, sand particles compacted, and as they remove upper, their density decreases, and permeability of the formation increases.

Having located the origin of the coordinate axis z in lower part the filter and directing the axis vertically upwards, as in Fig. 4, in the first approximation we accept the change in permeability as linear

$$k_2(r_c, z) = k_3 + (k_4 - k_3)\,\frac{z}{h} \tag{17}$$

Pick out from the formation at the distance z an infinitely small layer of thickness dz (Fig. 4).

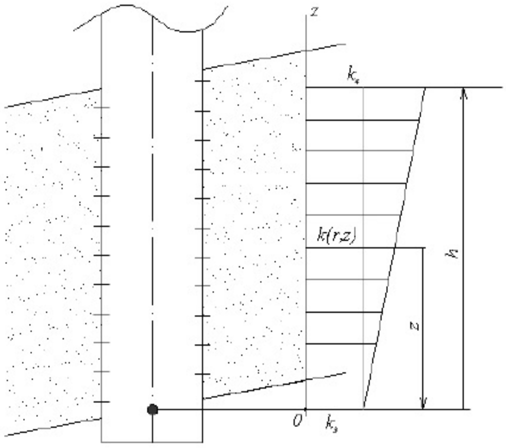

Fig 4. Calculation scheme.

Since there is no fluid displacement in vertical direction, in this layer the fluid filtration can be considered flat-radial.

Then the change in the permeability in the elementary layer in the vertical direction can be ignored and fluid inflow into the well per unit time can be determined by the formula

$$Q = \frac{2\pi}{\mu} \int_0^h k_2(r_c, z) \cdot \frac{P_c - P}{\ln\left(k_0 \frac{r_c}{R_1}\right)} \left(\frac{R_1 - k_0\, r_c}{R_1 - r_c}\right) dz \tag{18}$$

Substitute P and $k_2(r_c, z)$ from the expressions (14) and (17) in formula (18) , integrate the obtained expressions from 0 to h. Then we make numerical calculation for the following values of parameters:

$$R_1 = 5 \div 80m; k_0 = \frac{k_1}{k_2} = 1 \div 10; P_k = 5 \cdot 10^6 Pa;$$

$$\mu_H = 10^{-3} Pac; R_k = 100m;\ r_c = 7,5 \cdot 10^{-2} m; h = 30m.$$

The result of calculations are in Fig 5.

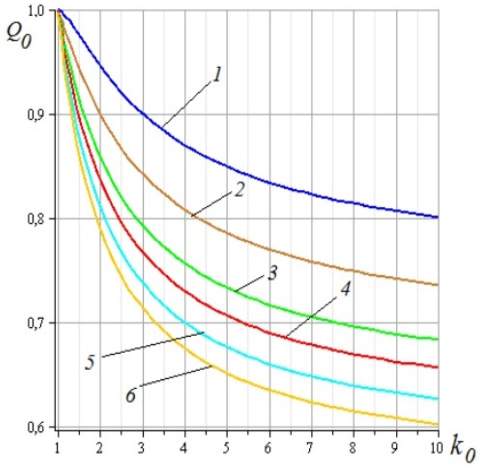

Fig 5. The graph of dependence of the ratio of debit in the presence of a filter to the debit without a filter on the ratio of pernecability coefficients of zones in the case of taking into account inhomogeneity of the second zone of the formation in radial and vertical directions at different values; $R_1 : 1 - R_1 = 5m$; $2 - R_1 = 10m$; $3 - R_1 = 20m$; $4 - R_1 = 30m$; $5 - R_1 = 50m$; $6 - R_1 = 80m$.

As can ve scen from fig 5, when the permeability of the second zone of the formation changes in vertical direction as well, then increeasing the radius of the zone dividing contours the inflow into the well per unit time also diminshes.

Moroewer, decline rate slow down even more. Decreasing the permeability around the well zone, at first inflow drops shapply and then its decline decrases.

We now find sand accumulation time in the well bottom zone. Taking into account slowness of sand accumulation, we accept fluid inflow into the well per a unit time in the first approximation as constant. Then the mass of the accumulated sand brought by the fluid per unit at time can be determined by the formula

$$2m_0\rho h\pi R_1\frac{dR_1}{dt} = \gamma Q \tag{19}$$

Integrating expression (19) , we obtain

$$T = \frac{\rho m_0 {R_1}^2}{\gamma Q} \tag{20}$$

where γ is mass concentration of sand in the produced fluid, ρ is sand density $Q$is fluid inflow into the well per unit time , T is time of sand accumulation in bottom hole zone for the given radius.

Calculation of accumlation time by formula (20) allowing for formula (18) for the given above values f the parameters and various values of sand concentration are in Fig.6.

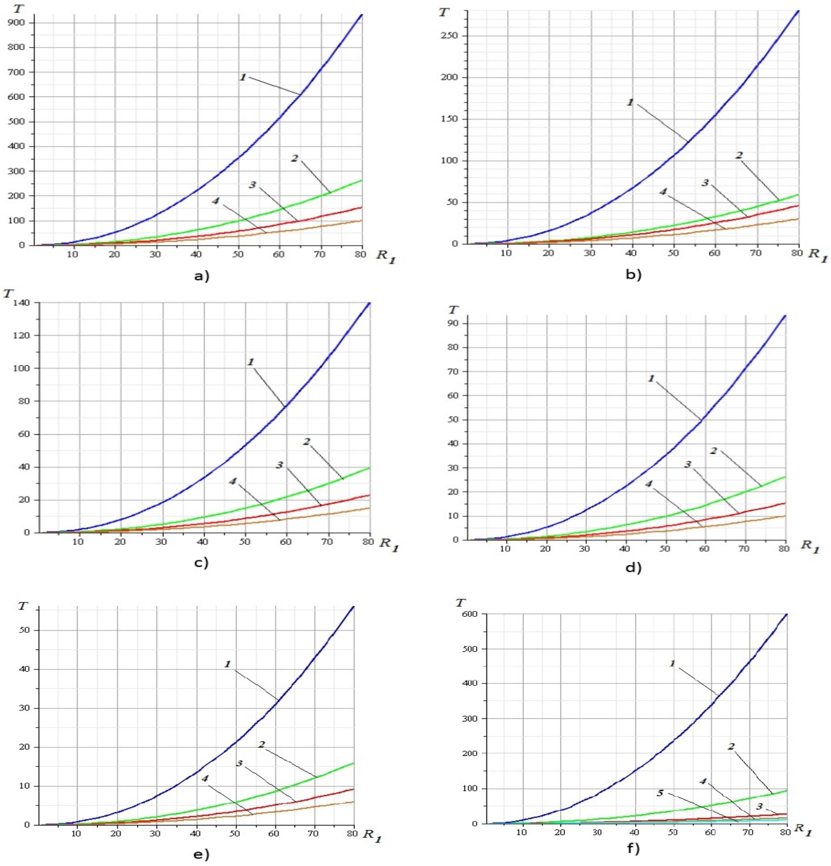

Fig 6. The graph of dependence of time of sand accumulation around the wellbore on accumulation zone radius at different values of mass inflow of sand per unit time for $k_1 = 3 \cdot 10^{-14} \div 10 \cdot 10^{-14}$; $a)\gamma = 3kq/m^3$; $b)\gamma = 10kq/m^3$; $d)\gamma = 20kq/m^3$; $c)\gamma = 30kq/m^3$; $e)\gamma = 50kq/m^3$; $f)\gamma = 30kq/m^3$ the graph was shown at $k_1 = 1 \cdot 10^{-14}$ as well)

As can be seen from Fig.6, with a decrease in the permeability of the second zone of the formation, other equal conditions, sand accumulation sharply increases. For example, for $\gamma = 30$ and $\frac{k_1}{k_2} = 3$, for sand accumulate around the wellbore of radius of 80 m, takes 90 days, while for $\frac{k_1}{k_2} = 10$ this time is 18 days. Therewith, fluid inflow into the well as can be seen from Fig.5 decreases by 5 times. It should be noted that the obtained graphs allow to determine efficiency of the use of filters i.e.in the wells with abundant sanding availability of a filter can reduce to rapid clogging of the bottomhole zone of the well with sand, and consequently to decrease in fluid inflow into the well up to its complete extinction i.e. from the obtained formula (20) one can get a criterion for the use of filters in oil production.

4. Accounting for the presence of plug in the pipe string

We consider the case when sand fractions are collected in the cavity of the pipe string. Then the liquid fluid occurs in three different sites of the string (Fig. 7):

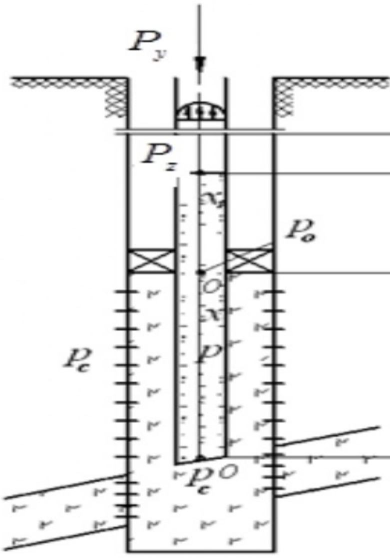

Fig 7. Calculation scheme.

- motion of fluid in a pipe clogged with sand and with permeable wall (the presence of a filter);
- motion of fluid in a cavity clogged with sand;
- motion of fluid in a sand free cavity.

The equation of fluid motion in a pipe with permeable wall is of the form [18]:

$$\lambda \cdot (P - P_c) = -\frac{dQ}{dx} \tag{21}$$

Fluid flow in the cavity of the pipe plugged with sand can be determined by the formula

$$Q = -f \frac{k}{\mu} \frac{dP}{dx} \tag{22}$$

Substituting the expression (22) in formula (21), we obtain

$$\frac{d^2 P}{dx^2} - b^2 P = b^2 P_c \tag{23}$$

where $b^2 = \frac{\lambda \mu}{f k}$, $f = \pi r^2$, k is a permeability factor of the plug in the pipe .

The boundary condition

$$P\left.\right|_{x=0} = P_c \tag{24}$$

$$P\mid_{x=h}=P_0 \tag{25}$$

where h_1 is the heigut of the first side P_0.

The solution of (23), allowing for boundary conditions (24) , (25), of the form

$$P=\frac{P_0-P_c}{sh\,(bh)}sh\,(bx)+P_c \tag{26}$$

The liquid flow at the end of the first site can be determined by the formula

$$Q=-f\frac{k}{\mu}\frac{\partial P}{\partial x}\mid_{x=h} \tag{27}$$

Then substituting the expression (26) in formula (27), we get

$$Q=-\frac{k}{\mu}\pi r^2 b\,(P_0-P_c)\,cth\,(bh) \tag{28}$$

The fluid motion equation in the second site of the pipe string will be of the from [19]: (Fig.7)

$$\frac{d^2P_1}{dx_1{}^2}=0 \tag{29}$$

The boundary conditions

$$P_1\mid_{x_1=0}=P_0 \tag{30}$$

$$P_1\mid_{x_1=h_1}=P_z \tag{31}$$

The solution of equation (29), allowing for boundary conditions (30), (31), is of the form

$$P_1=P_0-\frac{P_0-P_z}{h_1}\cdot x_1$$

The fluid flow at the end of this site can be determined by the formula

$$Q=-f\frac{k}{\mu}\frac{\partial P_1}{\partial x_1}\mid_{x_1=h1} \tag{32}$$

From the expression (32) allowing for expression (31) we obtain

$$Q=\frac{k}{\mu}\pi r^2\frac{P_0-P_z}{h_1} \tag{33}$$

where h_1 is the height of the second site r is the radius of flow section of the pipe, P_0 and P_z are pressures.

The fluid pressure P_z at the final section of the second site can be determined from the formula

$$P=P_y+\rho gl+\frac{8lk}{r^2}\frac{P_0-P_z}{h_1} \tag{34}$$

The flow of fluid through the permeable pipe is determined by the formula (16). From the conditions of fluid flow continuity, from the expressions (16), (27) and (28), allowing for the expression (34), we obtain

$$P_c = \left[kr^2 b \cdot cth\,(bh)\, \frac{P_y + \rho g l}{1 + \left(1 + \frac{8lk}{r^2 h_1}\right) bh_1 cth\,(bh)} - 2k_2 h \frac{R_1 - k_0 r_c}{(R_1 - r_c) \ln\left(k_0 \frac{r_c}{R_1}\right)} \times \right.$$

$$\left. \times \frac{P_k \frac{k_0}{\ln \frac{R_k}{R_1}}}{\frac{k_0}{\ln \frac{R_k}{R_1}} - \frac{R_1 - k_0 r_c}{k_0 (R_1 - r_c) \ln\left(k_0 \frac{r_c}{R_1}\right)}} \right] \Bigg/ \left[- \frac{kr^2 b^2 cth^2\,(bh)}{\frac{1}{\left(1 + \frac{8lk}{r^2 h_1}\right)} + bh_1 cth\,(b \cdot h)} + k \cdot r^2 b \cdot cth\,(bh) - \right.$$

$$\left. -2k_2 h \frac{R_1 - k_0 r_c}{(R_1 - r_c) \ln\left(k_0 \frac{r_c}{R_1}\right)} \left(1 - \frac{\frac{R_1 - k_0 r_c}{k_0 (R_1 - r_c) \ln\left(k_0 \frac{r_c}{R_1}\right)}}{\frac{k_0}{\ln \frac{R_k}{R_1}} - \frac{R_1 - k_0 r_c}{k_0 (R_1 - r_c) \ln\left(k_0 \frac{r_c}{R_1}\right)}}\right) \right] \qquad (35)$$

Numerical calculation was carried out by formula (8) allowing for formulas (7) and the obtained expression (35) for the following values of parameters and various values of $\frac{k_4}{k_3}$:

$$k_0 = \frac{k_1}{k_2} = 1 \div 10; P_k = 5 \cdot 10^6\, Pa;\ P_y = 10^6 Pa; \mu_H = 10^{-3} Pac; R_k = 100m;$$

$$r_c = 7,5 \cdot 10^{-2} m; h = 30m; r = 3 \cdot 10^{-2} m; g = 10m/c^2;\ \rho = 860kq/m^3;$$

$$h_1 = 5m; l = 2000m; k_1 = 10^{-13} - 10^{-12}\ m^2; \lambda = 0.1\, m^2/c \cdot Pa;$$

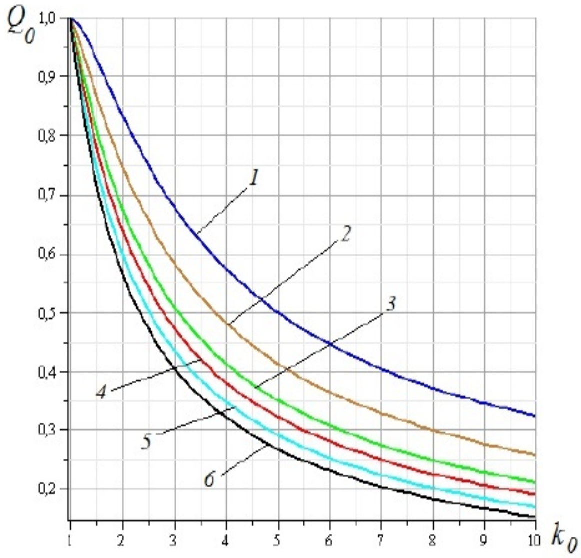

Fig 8. The graph of dependence of the ratio of debit in the presence of a filter on the ratio of permeability coefficients of zones in the case when the pipe string cavities are plugging with sand

at different values of: $R_1 : 1 - R_1 = 5m; 2 - R_1 = 10m; 3 - R_1 = 20m; 4 - R_1 = 30m;$
$5 - R_1 = 50m; 6 - R_1 = 80m.$

The results of calculations are in Fig.8. As can be seen from Fig.8, under other equal conditions, when the inflow into pipe string cavity is clogged with sand, the liquid inflow into the formation per unit time decreases for 1.75 times

Conclusion. Based on the carried out investigations, analytic expressions that allow to determine the criterion for the use of filters in oil and gas wells and to assess efficincy of their use, were obtained.

Acknowledgement. This work was financed by the Scientific Fund of the State Oil Company of the Republic of Azerbaijan – Grant – N0 19 LR.

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Received 23 January 2022
Accepted 24 March 2022