

**FILTRATION IN ANTHROPOGENICALLY MODIFIED
NEAR WELL-BORE ZONES AND WELL PRODUCTIVITY**

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Abstract

The models taking into account the influence of the structure of the borehole vicinity areas on the productivity of wells are suggested. There were considered the influence of such factors as near-well bore zone invasion, filtration deformation of matrix solid material, jamming of fluids in pores and thermal expansion of rocks. There were obtained formulas which allow to analyze both combined and separate influences of these factors on well productivity, and the necessity for such modeling in the process design was shown.

Key words: near wellbore zone, phase permeability, well production, filtration, thermal methods, fluid's jamming.

1.SIMULATIONS OF THE PERMEABILITY CHANGE IN NEAR WELLBORE ZONE

There occur technological changes of natural formation properties during construction and exploitation of wells, and a system of near well bore zones with special condition of filtration is formed. [7] Near well bore zones cause changes of filtration laws, considerable losses of formation energy and decrease in well productivity with respect to the natural state of formation – without near well bore zone changes. A wide set of methods and technologies to impact on the borehole area were developed. But these technologies don't take into account non-linear filtration caused by radial changes of permeability in near well bore zone, by permeability of the target fluid dependence on filtrational compaction and anthropogenically modified near well bore zones. Non-linear filtration and complex mechanism of formation damage and near well bore zone state changes in different geological and technological conditions, cause low technological efficiency of existing enhanced oil recovery technologies.

In spite of a large number of near well bore zone changes mechanisms there is a certain generality of it. Blocking of pores by different solid particles is basic formation damage mechanism [7]. Here we may combine factors such as anthropogenic changes of the natural microstructure by particles of technological fluids, sedimentation of gums and pyrobitumens in pores, dispersion of clayey minerals by low-mineralized solutions, blockage of pores by bacteria, chemical reactions etc. These factors lead to the formation of near well bore zones at the stages of construction and development of wells, and determine the patterns of filtration during the operation of wells.

In addition, there is another group of factors playing a role. They are related to filtrational deformation of the matrix solid material under the action of the depression and temperature variations as a result of the thermal methods application. These factors determine thermobaric stresses and may cause changes in permeability of the near well bore zone (for example, Zybza deposit development [2]). Thereby, change of the near well bore zone permeability is a complex, multiphase process.

Permeability of the target fluid in near well bore zone is determined by a the structure of pore space, saturation of the pore space by stationary (residual) phase, relation between target and following fluid, type of wettability and–some other factors. There–occur changes of all factors listed above during construction of wells and well testing, and at the stage of well operation new technogenic target

permeability is formed in near well bore zone. In the case of single-phase filtration permeability of the target fluid is determined by microstructure changes and stationary saturation in near well bore zone.

Traditionally, permeability changes in near well bore zone under action of first group of factors (formation damage), was simulated by a step function. Permeability in near well bore zone was considered constant and different from other parts of formation. But many researches show that permeability changes caused by formation damage may have many types considerably different from a step function [7]. To receive solutions that can be applied in any cases we will simulate formation damage influence by general function of coordinates $A(x,y,z)$, in radiate case it will be function $A(r)$.

Thereby, formation damage influence on permeability will be stated by the following formula [11]

$$\frac{k(r)}{k_0} = \begin{cases} A(r), & r_c < r < r_{fd} \\ 1, & r_{fd} < r < r_k \end{cases}, \quad (1)$$

k_0 – target permeability of formation without formation damage, r_c and r_k – well radius and external boundary of formation radius, $A(r)$ - non-dimentional function of radius which describes permeability change, r_{fd} – radius of formation damage zone, which describes distance at which natural permeability of formation and permeability of near well-bore zone are equal.

1.1 Influence of filtrational deformation of the matrix solid material on the permeability.

Filtrational deformation of the matrix solid material σ_{ij} is determined by two factors: existing rock pressure and deformation caused by changes of current pressure [9], so

$$k = k_0 f^*(\sigma_{ij}, p) \quad (2)$$

Stressed state of the near well bore area is formed under action of rock pressure as a result of the stresses concentration in well vicinity. It causes changes of stresses in radial direction. Modified stressed state—is formed in the stage of construction, completion and well testing. During well operation effect of the stressed state in well vicinity is revealed by inherited from previous stages stress distribution subject to coordinates (or radius in radient case). So in the case of exploitation of wells with stationary depression, function f^* may be split into two function, first depending on radius only and second depending on pressure only, and formula (2) then transforms to

$$k = k_0 f^*(\sigma_{ij}(r), p) \quad (3)$$

Now we will consider permeability changing under depression. For taking into account pressure influence on the permeability, different laws of permeability dependence on pressure drop are employed, for example exponential or power laws [3]. Special researches show, that for different types of formation, permeability-pressure dependence may be of various types and even nonmonotonic [5],[8].

In general case there will be considered permeability dependence on pressure drop simulated by a function $f(p)$

$$k / k_0 = f(p) \quad (4)$$

Subject to (3) and (4), relation (2) may be rewritten as

$$k = k_0 f_\sigma(r) f(p), \quad (5)$$

$f_\sigma(r)$ – function independent of current pressure.

1.2 Temperature influence.

Permeability dependence on temperature, according to [1], may be denominated as

$$k^* = k(T_0) \exp \left[-\frac{(3-\bar{m})}{\bar{m}} \beta (T - T_0) \right] \quad (6)$$

$\bar{m}$ – average porosity, β – const.

And a temperature may depend on coordinates, in radiate case $T=T(r)$.

So, with formulas (1), (2), (6), expression for filtration phase permeability can be derived, which takes into account formation damage expressed by formula

$$k = k^* [T(r)] f_{\sigma}(r) f(p) A(r) \quad (7)$$

Thus, radiate function in addition to formation damage will include permeability changing as a result of difference in thermal expansion efficiencies of constituent stratum minerals and stress changing in near well bore zone.

$$A^* = A(r) f_{\sigma}(r) \exp \left[-\frac{3-\bar{m}}{\bar{m}} \beta (T(r) - T_0) \right] \quad (8)$$

Accordingly, plugging it into (7), we get

$$k = k_0 f(p) A^*(r) \quad (9)$$

Expression (9) is correct when conditioning processes of formation damage, deformation and heat exchange already happened at the stage of well construction and processes of permeability changing caused by pressure change is controlled by the current operation conditions of well (depression, repression, viscosity of target fluid and others).

1.3 Fluid's jamming influence.

As was noted in p.2 one more factor which may cause permeability change is blocking of pores by stationary fluids.

In natural conditions quantitative characteristics of the immovable phases (water, oil) are controlled by physicochemical processes running in geological time (hundreds of thousands years). These values got stabilized and values of residual (relict) immovable saturations are related only to geological features of collectors. During construction of wells and while execution of geological and technological activities there occur processes of oil displacement by filtrates of process liquids and processes of filtrates displacement by oil. Filtration processes cause formation of immovable phases which were absent in natural conditions.

Generalization of experimental investigations allows us to determine regimes of filtration and formation of jammed phases [10]. The first (capillary regime) is characterized by a constant value of residual saturation at low values of capillary number. When the capillary number reaches its critical values N_{c1} , hydrodynamic pressure on the large globules becomes greater than the capillary forces and they begin to break up, with the part of small globules becoming mobile. And residual oil saturation decreases (capillary-pressure regime). Upon reaching the critical number N_{c2} , all capillary jammed oil is washed out of the pores (automodel regime). In the wide range of permeability (from 40,8 to 2180 mD), value of the first critical number N_{c1} is $2.7 \cdot 10^{-5}$ - $4.9 \cdot 10^{-5}$ [4]. Depending on the filtration regime, residual oil saturation s_{or} is given by [6]:

$$s_{or} = \begin{cases} s_{or}^{\max}, & N_c < N_{c1} \\ 1 - s_{wr} - CN_c^\delta, & N_{c1} < N_c \leq N_{c2} \\ s_{or}^{\min}, & N_c > N_{c2} \end{cases} \quad (10)$$

Where C is a coefficient determined by the reservoir properties, δ is a coefficient determined by the structure of the pore space, s_{wr} is the coefficient of residual water saturation (with jamming oil phase).

Generalizing this idea to the case of washed stratum, for water phase permeability we obtain

$$k_f = k(r, p) f_w(s(N_c)), \quad f_w(s) = D(s - s_{wr})^\beta \quad (11)$$

where $k(r, p)$ is permeability change, which takes into account the factors of formation damage, deformation and thermal expansion (6), s – water saturation of washed zone, $s = 1 - s_{or}$, $f_w(s)$ – function of the relative phase permeability for flood water near well, D and β are constants.

The expression for the water saturation in fully flushed zone s , dependent on the N_c , may be obtained from (11), taking into account that $s = 1 - s_{or}$. Dependences $k(r, p)$ in the relationship (9) are obtained from experiments on single-phase filtration, and dependences of (11) type are obtained from the experiments of the displacement of one phase by another one, not mixed with first phase.

Thus the dependence of the relative water phase permeability on the capillary number can be written as

$$f_w(N_c) = \begin{cases} f_2, & N_c > N_{c2} \\ BN_c^\alpha, & N_{c1} < N_c < N_{c2} \\ f_1, & N_c < N_{c1} \end{cases}, \quad (12)$$

where N_{c1} and N_{c2} – boundary values of the capillary number, which characterize the regime of jammed oil formation, f_1 and f_2 – values of the relative phase permeability in automodel and capillary regimes of jammed oil formation, $B = AC, \alpha = \beta\delta$.

Boundary values of the capillary number are reached at some fixed distance from the wellbore wall, and form different zones. Let us denote the size of zones by r_1 and r_2 , i.e. $r = r_1$ at $N_c = N_{c1}$ and $r = r_2$ at $N_c = N_{c2}$. Using conventional expression for the capillary number $N_c = k_f \Delta p / (\sigma L)$, where k_f – phase permeability for water, Δp – pressure drop across the sample length L, σ – interfacial tension at the boundary water-oil and expressing speed as a function of pressure gradient, we obtain the dependence of permeability on radius in the following form:

$$f_w(r) = \begin{cases} f_2, & r \in D_1 \\ B \left(\frac{k_f}{\sigma} \frac{dp}{dr} \right)^\gamma, & \gamma = \beta\delta, B = CD, r \in D_2 \\ f_1, & r \in D_3 \end{cases} \quad (13)$$

$$D_1 = \{r_c \leq r \leq r_2\}, D_2 = \{r_2 < r < r_1\}, D_3 = \{r_1 \leq r \leq r_k\}$$

Schematically this dependence is shown on the Fig 1

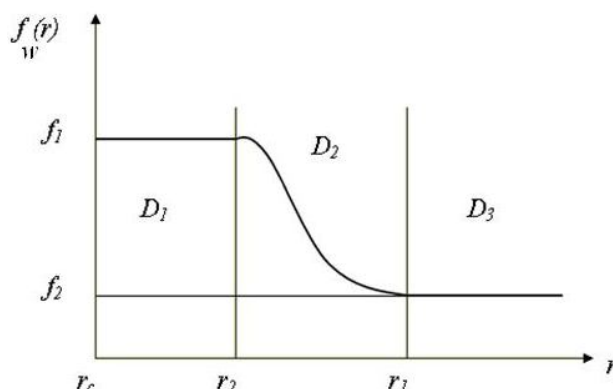


Fig. 1 Regimes of filtration and formation of jammed phases.

D_1 - automodel regime, D_2 - capillary-pressure regime, D_3 - capillary regime.

2.DISTRIBUTION OF PRESSURE IN COMPLICATED NEAR WELL BORE ZONES

In general case, i.e. taking into account formation damage, filtrational deformation, thermal expansion, and existence of the jammed phase, expression for filtration rate will look like

$$\omega(r, p, gradp) = \frac{k_f(r, p, gradp)}{\mu} \frac{dp}{dr} \quad (14)$$

From the continuity equation $div\omega=0$ with expression for the rate of filtration, we obtain the system to solve the problem.

For the capillary-pressure regime of displacement ($N_{C1} < N_C < N_{C2}$), zone 2, the following equation is correct:

$$\frac{d}{dr} \left[r(A^*(r)f(p) \frac{dp}{dr})^{1/(1-\gamma)} \right] = 0 \quad (15)$$

In that part of reservoir, where capillary ($N_C < N_{C1}$, zone 3) and automodel ($N_{C2} < N_C$, zone 1) regimes operate, we obtain next expression after canceling constants

$$\frac{d}{dr} (rA^*(r)f(p) \frac{dp}{dr}) = 0 \quad (16)$$

Let's define the following conditions on the well and circuit:

$$p|_{r=r_c} = p_c, \quad p|_{r=r_k} = p_k \quad (17)$$

In addition we must define conditions on the zone's boundaries, which indicate a regime change (the capillary number reaches its critical value):

$$N_C = \frac{k_f(p, r)}{\sigma} \frac{dp}{dr} \Big|_{r=r_i} = N_{Ci} \Rightarrow \frac{dp}{dr} \Big|_{r=r_i} = \frac{N_{C2}\sigma}{k_f(p, r)} \quad (18)$$

Thus, we have a system to solve problem (15)-(16) with boundary conditions (17), which determines the distribution of pressure in reservoir. It's convenient to use the following integral function to solve it:

$$\Psi^*(r) = \int_{r_2}^r \frac{dr}{r^{(1-\gamma)} A^*(r)}, \Phi(p) = \int_{p_c}^p f(p) dp \quad (19)$$

In general case it is impossible to obtain an analytic solution of this system. The pressure distribution for different states of near well bore zone was obtained for special cases. (Fig. 2) [10]

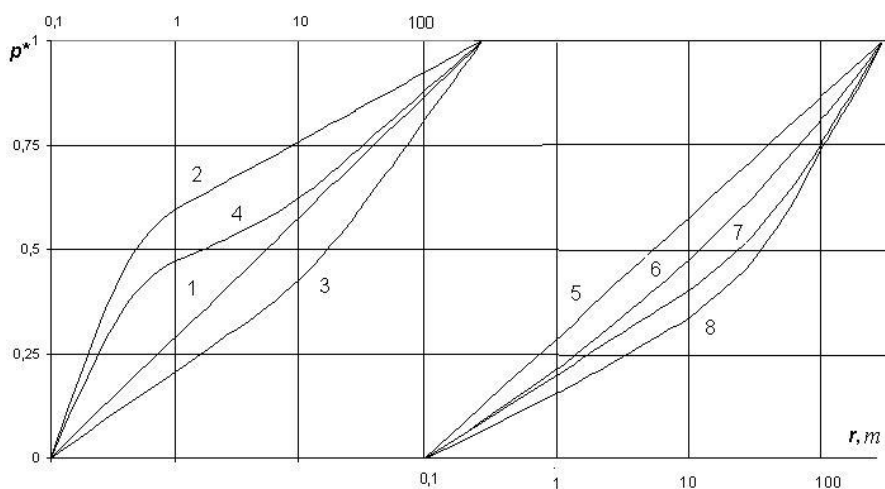


Fig.2 radial distribution of pressure. $p^* = (p-p_c)/(p_k-p_c)$; $f(p) = 1$ (curves 1-4), $\gamma = 0$, $A^*(r) = 1$ (1,5), $A^*(r) \neq 1$ (2); $\gamma \neq 0$, $A^*(r) = 1$ (3), $\gamma \neq 0$, $A^*(r) \neq 1$ (4); $A^*(r) = 1$ (curves 5-8), $\gamma = 0$, $f(p) \neq 1$ (6); $\gamma \neq 0$, $f(p) = 1$ (7); $\gamma \neq 0$, $f(p) \neq 1$ (8).

As one can see from the graph, subject to condition of near well bore zone and the factors influencing its permeability, pressure distribution and hence pressure gradient near the well may vary significantly, what consequently affects the productivity of wells.

3.NEAR WELL BORE ZONE INFLUENCE ON WELL PRODUCTIVITY IN SPECIAL CASES..

Expression for well productivity which takes into account permeability change in near well bore zone caused by factors was described above, will look [11]

$$Q = 2\pi h \frac{k^*(T_c)}{\mu(T_c)} \frac{\Phi(p_c, p_k)}{\Psi^*(r_c, r_k)} \quad (20)$$

Where functions Φ and Ψ^* determined by expressions (19).

These solutions allow analysis of the influence of permeability change factors in the near well bore zone on the well productivity. Now we will consider separately the influence of each of them.

Permeability change along the radius is determined by two factors: formation damage function $A(r)$, deformation function $f_\sigma(r)$ and temperature change of permeability in the form (6). To research the influence of the parameters that determine the function $A^*(r)$ (radius of formation damage and the

value of this function on the well $A^*(r_c)$ on productivity, we will consider the ratio of flow rates of contaminated and clean reservoirs. Excluding the impact of filtration deformation and temperature, and taking into account formulas (20), it becomes

$$Q/Q_0 = \frac{\ln(r_k / r_c)}{\Psi(r_c, r_{fd})}, \quad (21)$$

where

$$\Psi(r_c, r) = \int_{r_c}^r \frac{dr}{rA(r)}$$

Thus, the effect of formation damage on the productivity depends on the type of the function $A(r)$ (integral function Ψ depends on it) and the radius of formation damage r_{fd} .

On the Fig. 3 you can see graphs showing dependence of the value Q/Q_0 on the radius of the perturbed zone for various formation damage functions $A(r)$.

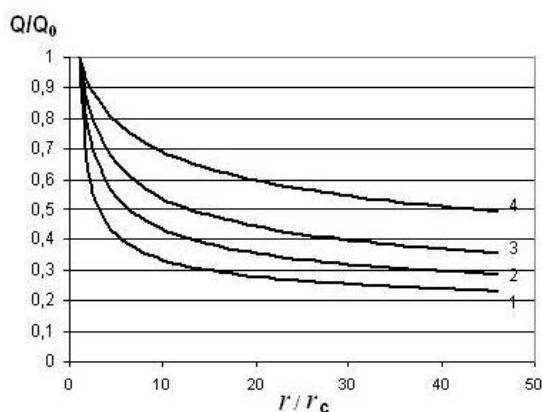


Fig.3. Relational productivity dependence on type of $A(r)$ function. 1 – A-step function; 2 – A depends on r^2 ; 3 – A-linear function; 4 – A depends on $\sqrt{r}$

One can see that even with a small radius of the perturbed zone, the productivity for the different dependences may vary significantly. This shows the necessity of more detailed study of the impact of formation damage on the permeability in the near wellbore zones.

3.1 Temperature.

Now we will consider the change of production with respect to its initial value (at $T = T_0$):

$$Q/Q_0 = \frac{k^*(T)}{k^*(T_0)} \frac{\mu(T_0)}{\mu(T)} \frac{\ln(r_k / r_c)}{\Psi^*(r_c, r_k)} \quad (22)$$

To heat the reservoir efficiently we need to increase production as temperature increases, i.e. $Q/Q_0 > 1$, so we have

$$\frac{k^*(T)}{k^*(T_0)} > \frac{\mu(T)}{\mu(T_0)} \frac{\Psi^*(r_c, r_k)}{\ln(r_k / r_c)}, \quad (23)$$

and with (6), we obtain

$$\exp\left[-\frac{(3-\bar{m})}{\bar{m}}\beta(T-T_0)\right] > \frac{\mu(T)}{\mu(T_0)} \frac{\Psi^*(r_c, r_k)}{\ln(r_k / r_c)}$$

Thus, despite the reduction in oil viscosity, in the case of failure of this relation, heating of the reservoir may be ineffective due to changes in permeability caused by thermal expansion of rocks. This effect is illustrated by Fig.4 with graph of the Q/Q_0 dependence on temperature.

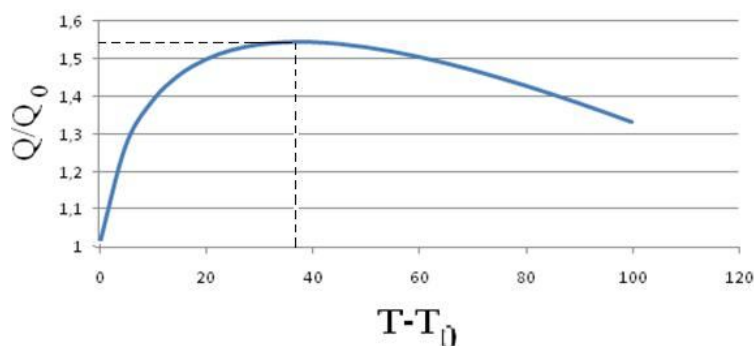


Fig 4 Production depends on temperature change.

The maximum point, i.e. the maximum temperature for reservoir heating to be effective, is determined by the condition on the function $Q(T)$ to have zero derivative:

$$dQ/dT = 0$$

3.2 Filtrational compaction.

Next considered factor of permeability change is filtration compaction. We assume, for convenience, the absence of other factors of permeability change in near well bore zone. Then the expression (20) can be rewritten as

$$Q = 2\pi h \frac{k_0}{\mu} \frac{\Phi(p_c, p_k)}{\ln \frac{r_k}{r_c}} \quad (24)$$

In contrast to the incompressible layer, in this case the curves of the production dependence on pressure drop are not linear. This can be seen on the Fig.5 that shows the indicator diagrams for different types of the permeability dependence on pressure.

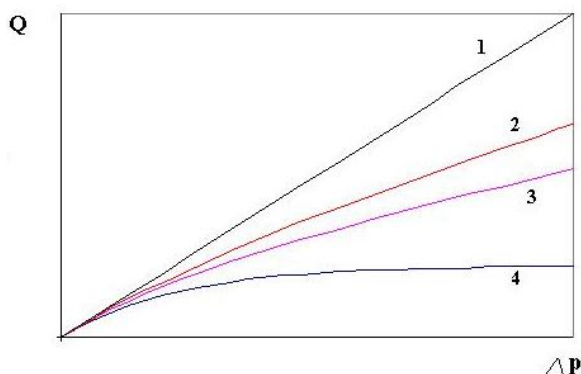


Fig 5 Production depends on near wellbore zone conditions 1. incompressible layer; 2. $k/k_0=(1+BLn(p/p_k))$; 3. $k/k_0=(p/p_k)^a$; 4. $k/k_0=\exp(-\alpha(p_k-p))$.

To analyze the influence of a filtration compaction on productivity it is appropriate to take the ratio of Q to Q_0 , where Q_0 is production of the well for incompressible layer. Then, after the reductions, from (20) we have

$$\frac{Q}{Q_0} = \frac{\Phi(p_c, p_k)}{p_k - p_c} \quad (25)$$

where the function Φ is defined by (9).

Curves of production dependence on pressure drop with respect to production without consideration of the effects of compressibility, are presented in Fig.6.

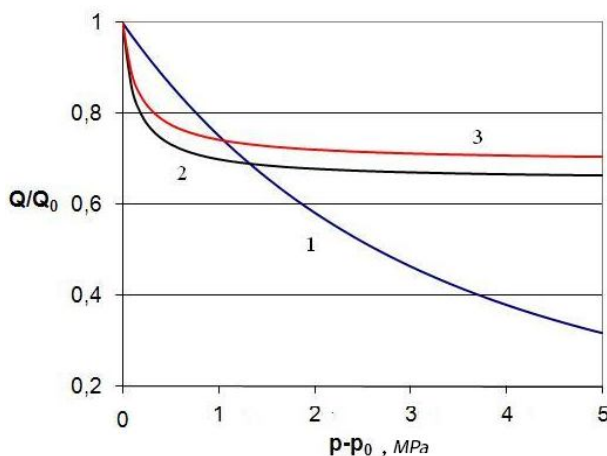


Fig.6. 1. $k/k_0=\exp(-\alpha(p_k-p))$; 2. $k/k_0=(p/p_k)^a$; 3. $k/k_0=(1+BLn(p/p_k))$

It is shown that for different types of relationships (1-3) the loss of production due to the loss of permeability, caused by filtration skeletal deformations of rocks, may vary several times, what shows the necessity for careful consideration of this effect in technological calculations.

4.OIL JAMMING

Now we will consider the case of oil displacement by water pumped into injection wells. After washing the near well bore part of the reservoir, pressure is stabilized and the expression for the injection wells becomes

$$Q = \left[\frac{2\pi r_c h k_f(r, p, \text{grad} p)}{\mu} \frac{dp}{dr} \right]_{r=r_c} \quad (26)$$

Pressure distribution and hence its gradient at the well, will then be determined from the system (2.2-2.5). In general case it is impossible to obtain an analytic solution of this system. Construction of numerical solutions makes it possible to analyze the influence of the jammed phase on the intake capacity of wells [10].

Constructed curves of intake capacity dependence on repression for different states of the near well bore zone are presented on Fig. 7.

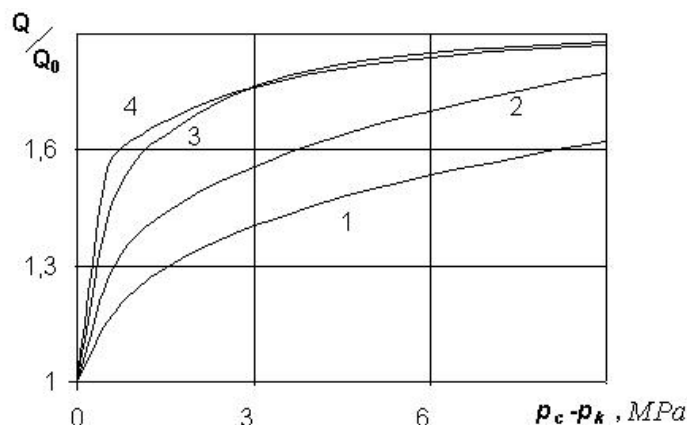


Fig. 7 intake capacity dependence on repression for incompressible layer.

$A(r) \equiv 1$; value of the parameter γ (formula 2.13): 0.4; 0.5; 0.6 (curves 1-3); $A(r) \neq 1$, $\gamma = 0.6$ (curve 4).

Dependence of the intake capacity on the pressure is nonlinear and this nonlinearity increases with increase of the coefficient γ (Fig. 6). At the same time as pressure drop increases, this dependence asymptotically approaches the linear one.

Comparison of the curves 3 and 4 shows that the difference between the values of Q/Q_0 for clean and damaged reservoir does not exceed 10%. Therefore, the influence of fluids jamming and formation damage on the productivity of wells can be considered separately. Thus, the general problem of joint allowance of formation damage and jamming is divided into two special cases, making it easier to find the solution.

To analyze the influence of the filtrational compaction on the intake capacity in the case of wetting phase jamming, we'll compare intake capacity with the dependence of permeability on the pressure in the exponential form $k = k_0 \exp(-a_p(p_k - p))$ for different coefficients a_p , including when $a_p = 0$ (incompressible layer).

Let us consider the dimensionless quantity Q/Q_0 , where Q_0 is well productivity in the case of incompressible layer without the presence of jammed phase:

$$Q/Q_0 = f_2 \frac{\Phi(p_c, p_2)}{p_k - p_c} \frac{\ln(r_k / r_c)}{\ln(r_2 / r_c)} \quad (27)$$

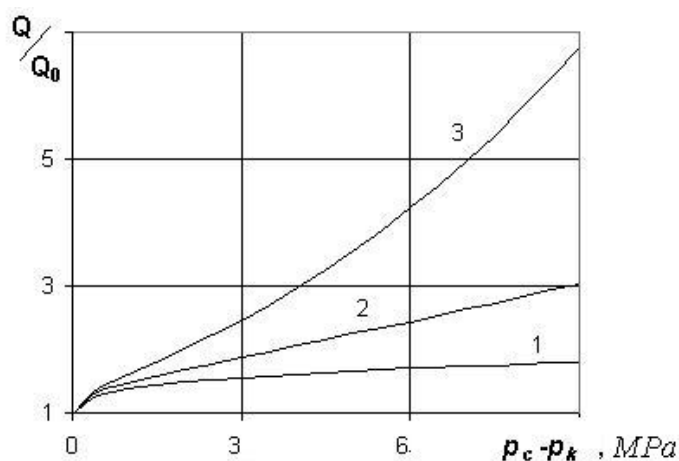


Fig 8. Intake capacity dependence on the pressure drop for compressible layer.

$$k = k_0 \exp(-a_p(p_k - p)), \quad a_p = 0; 0.02; 0.05 \text{ (curves 1-3); } \gamma = 0.5.$$

For a sufficiently large pressure drop, even for small values of a_p , compressibility leads to a change of intake capacity by several times.

4.1 Filtrate jamming in near well bore zone of production wells.

Now we will consider the case, where in the process of formation exposing or well killing there occurs either jacking of process fluid in near well bore zone or injection of filtrate into this zone.

Let us denote the size of the zone of filtrate jamming by r_p , and suppose that only automodel and capillary-pressure modes can be achieved. Then, using the proposed model of the residual saturation (in this case it would be a residual saturation of filtrate) dependence on the capillary number, we obtain

$$f_{or}(r) = \begin{cases} f_1, & r < r_1 \\ BN_c^\alpha, & r_1 < r < r_p \\ f_2, & r > r_p \end{cases}, \quad (28)$$

Where $f_{or}(r)$ is relative permeability of oil in the presence of jammed filtrate (see Section 2), B and α are constants, r_p is the size of the zone of penetration of filtrate. Graphically, this is illustrated in the figure 9.

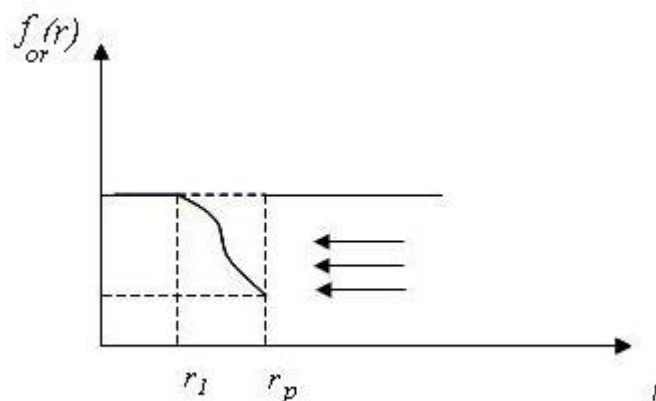


Fig.9 Filtration zones in the case of filtrate jamming in near well bore zone.

The system of equations for solving the problem is similar to the case of oil displacement by water, with the only difference being that in this case the size of the zone of penetration of filtrate is known and the condition that the capillary number reaches the first critical number is not necessary.

The production will be calculated by the formula (26), and in this case it is converted to the form

$$Q_0 = \frac{2\pi h k_0}{\mu} \frac{p_k - p_c}{\Psi(r_c, r_k)}, \quad (29)$$

before processing of the zone and

$$Q = \frac{2\pi h k_0}{\mu} f_1 \frac{p_1 - p_c}{\Psi(r_c, r_1)}, \quad (30)$$

after processing, with jammed filtrate in the zone (r_1, r_p) .

Unknown value of radius of the automodel regime (r_1) is calculated from the boundary conditions and equality of the capillary number to second the critical number at this point (equations similar (17)-(18) for the respective zones of the present case).

Below are shown the graphs of the ratio of productions for contaminated and uncontaminated formation versus pressure drop after processing the near well bore zone.

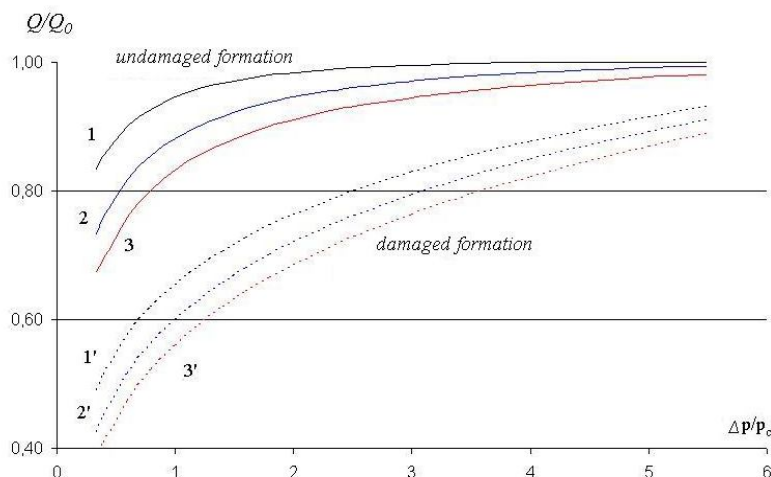


Fig.10 Change of the production as a result of jamming in various states of the near well bore zone.
(Q_0 -production till kill (or processing))

Values of the radius of the zone of penetration $1,1'$: $r_p/r_c=20$; $2,2'$: $r_p/r_c=40$; $3,3'$: $r_p/r_c=60$.

The influence of formation damage on the production in the case of a jammed filtrate or process fluid is smaller than that in the case of single-phase filtration.

CONCLUSIONS

1. We developed a set of hydrodynamic models of the influence of changes in near well bore zones on the productivity of wells, allowing to explicitly take into account the following: complex mechanism of formation damage, change of the permeability of the near well bore zones caused by capillary jamming of wetting and nonwetting phases.
2. The contribution of different mechanisms of changes in the natural filtration properties of the reservoir to the change in productivity of wells in the complicated near well bore zones is studied.
3. It is shown that the neglect of the real structure of the near well bore zones can lead to errors in determining of the productivity by several times.
4. Non-linear character of intake capacity dependence on the pressure drop is justified.
5. It is shown that the killing of a well while processing of near well bore zone can lead to productivity decrease due to filtrate jammed in the pores.

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