Transactions of NAS of Azerbaijan, Issue Mechanics, **37** (7), 86–96 (2017).
Series of Physical-Technical and Mathematical Sciences.

Gassy fluid flow in elastic-plastic deformable medium

**Azizaga Kh. Shakhverdiev · Geylani M. Panakhov ·
Eldar M. Abbasov · Yusif M. Sevdimaliyev**

Received: 10.05.2017 / Revised: 22.06.2017 / Accepted: 05.07.2017

Abstract. *Hydrocarbon saturated rocks, especially at great depths, undergo significant reversible, partially or completely irreversible deformations under high pressure and temperature effect. Deformations, in turn, cause corresponding alterations in the physical properties of reservoir rocks. The latter in some cases can become a serious obstacle for the flow of both Newtonian and non-Newtonian fluids. At considerable depths, under abnormally high formation pressures, and also with the breed plastic inclusions, such as, clays, salts, cracks, increases the degree of deformation and the probability of the initial pressure gradient occurrence, requiring the certain strategy adjustments in the hydrocarbons development. The problem was solved for steady state inflow of gaseous fluid to the borehole in underground formations with elastic, elastoplastic and plastic rocks. The relations can be used for interpreting well test data and specifies parameters of oil field development with the deformable elastoplastic reservoirs.*

Keywords. Fluid · flow · filtration · elastic-plastic · permeability · gassy fluids · pressure · porosity

Mathematics Subject Classification (2010): 76S05

A.Kh. Shakhverdiev
Russian Academy of Nature Sciences, Varshavskoye shosse, 8, Moscow, Russia Federationn
E-mail: ah_shah@mail.ru

G.M. Panakhov, E.M. Abbasov
Institute of Mathematics Mechanics, ANAS
B. Vagabzade 9, Baku, Azerbaijan
E-mail: eldar.abbasov@imm.az

Yu. Sevdimaliyev
Baku State University, Theoretical Mechanics and Mechanics of Solid Medium
Akademik Zahid Khalilov str, 23, Baku, Azerbaijan
E-mail: yusifsev@mail.ru

1 Introduction

It is necessary to take into account the real properties of the formation fluids and the porous medium itself at hydrodynamic calculations of the filtration of gassy oil in the porous medium.

The problems of the gaseous oil were set and developed in numerous research works. The steady flow of a gaseous liquid in an incompressible porous medium was considered by [10]. The process of filtration of gaseous oil through a non-deformable porous medium was considered by [21], taking into account only properties of formation fluids, and [9], [14, 15] studied of gassed liquid under conditions of an elastic filtration regime.

Many of the previous studies [1] have shown that the permeability of sandstones depends on the effective average stress and a sharp decrease in permeability is caused by the beginning of pore compaction [2].

Early experimental work [8, 18, 19, 7, 11, 13] pointed to important aspects of rocks compaction. Gorbunov and Shakhverdiyev [9, 14 – 17] also devoted his research to this issue using methods of theoretical analysis and experiments. Chaboche [5] investigated the dependence of stresses on the nonlinear behavior of weakly cemented sandstone. Benjamin Loret et.al. [3] studied the porosity and permeability reduction caused by elasticity-dominated deformation in sandstone reservoirs. In addition, they showed in their studies the dependence of the decrease in porosity and permeability, as well as the difference in mean effective stresses and pore pressure. Yarushina [20] analyzed the causes of deformation of unconsolidated sandstone. Binshan Ju [4] investigated mechanical disturbances associated with changes in strain and deformation during drilling and completion of wells and associated permeability changes. Irreversible or plastic deformations caused by the destruction of the pore space and repackaging the particles can lead to damage to the capacitive properties. Changes in permeability inevitably affect the efficiency of oil well production [12].

Indeed, reversible or elastic deformation in an oil reservoir occurs only when σ' is not up to σ'_c, and irreversible or inelastic deformation is more universal. In the experiments, it was shown that the inelastic deformation of porous rocks and the decrease in porosity is caused by an increase in the average stress [4, 6].

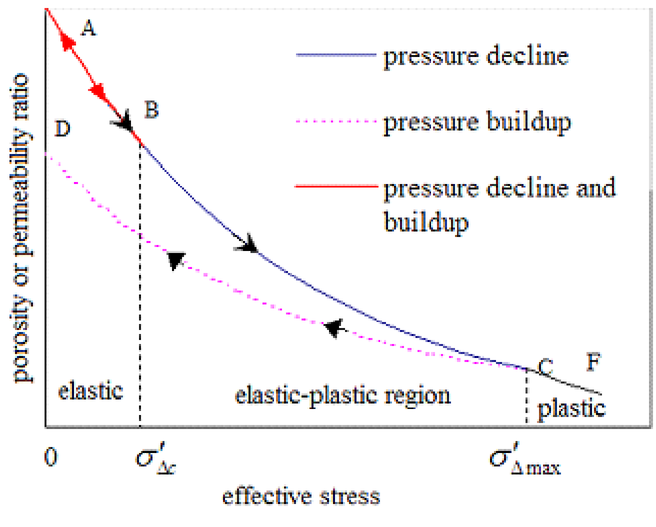

Fig. 1. The path of pressure change and the change of the ratio of porosity or permeability [1]

[1] * Binshan Ju Mathematical model and numerical simulation of multiphase-low in permeable rocks considering diverse deformation // Journal of Petroleum Science and Engineering 119 (2014). – pp. 149–155.

In our studies, the optimal bottom hole pressure was established, which ensures the greatest production rate for the flow of a homogeneous fluid under elastic, elastoplastic and plastic drives [16]. During the gassy fluid flow, it is also possible to set the optimum bottom hole pressure. The aim is to solve a number of theoretical and practical issues arising from the oilfields development under the conditions of the gassy fluids flow in elastic, elastoplastic and plastic rocks, based on the methodology of [10].

The gassy oil viscosity is not constant during flow in underground formation. As with the decrease in pressure in the formation, the gas previously dissolved in the oil is released, the viscosity increases. The dependence of the change in oil viscosity on pressure is shown in Fig. 2.

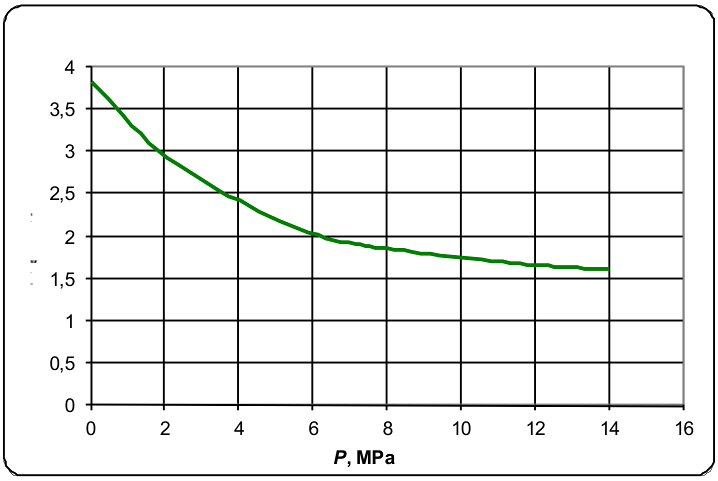

Fig. 2. Dependence of absolute oil viscosity on pressure change

As known from [21] investigations, in the development and exploitation of oil fields, the solubility coefficient is not constant, but varies depending on the pressure change (Fig. 3).

The curves presented in Fig. 2 and Fig. 3 are borrowed from [21]. This allowed us to compare the results obtained in this paper with the results of [21] in which the effect of deformations on the reservoir properties of reservoirs was not taken into account.

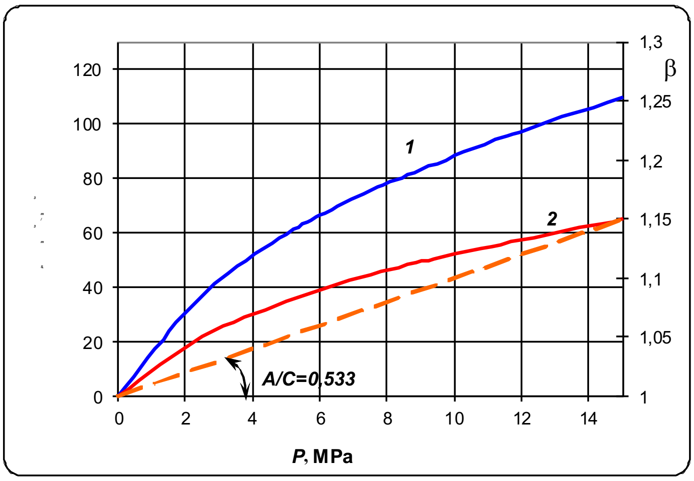

Fig. 3.Dependence of the solubility of gas S and the oil volume coefficient on the change under reservoir pressure.

In the present work, reversible, partially irreversible and completely irreversible changes in permeability are taken into account, depending on the pressure during the gassy fluid flow.

Taking into account the above-mentioned real oil and formation properties, we write out the equations for the steady-state filtration of gaseous oil, neglecting capillary and gravitational forces. For the case of filtration under the elastoplastic regime, the following system of equations is obtained:

$$\begin{gathered}\frac{1}{r}\frac{r}{dr}\left[\frac{K(P,a_k,\eta_k)F_o(S,P)\rho_o(P)}{\mu_o(P)}r\frac{dP}{dr}\right]=0;\\ \frac{1}{r}\frac{d}{dr}\left\{\left[\begin{array}{c}\frac{K(P,a_k,\eta_k)F(S,P)\cdot P}{\mu(P)RT\cdot Z(P)}+\\ \frac{K(P,a_k,\eta_k)F_o(S,P)\cdot PS_1(P)}{\mu_o(P)}\end{array}\right]r\frac{dP}{dr}\right\}=0;\end{gathered} \tag{1.1}$$

$\uparrow\downarrow K\left(P,a_k,\eta_k\right)=K_0\left[\phi_1\left(r\right)+\psi_1(r)\left(P-P_0\right)\right]$

$$\begin{aligned}&\phi_1(r)=\frac{\sqrt{\psi(r)}}{\sqrt{\psi(r)}+\frac{\eta_k}{a_k}\left[\sqrt{\psi(r)}-1\right]^{\,2}},\\ &\psi_1(r)=\frac{a_k\left\{\frac{\eta_k}{a_k}\left[\sqrt{\psi(r)}-1\right]^{\,2}+\frac{\eta_k}{a_k}\left[\sqrt{\psi(r)}-1\right]+\sqrt{\psi(r)}\right\}}{\sqrt{\psi(r)}+\frac{\eta_k}{a_k}\left[\sqrt{\psi(r)}-1\right]^{\,2}},\\ &a)\;\; P_+<P_c<P_0,\quad \psi(r)=1-\left\{1-\left[1+a_k(P_{+i}-P_0)\right]^{\,2}\right\}\frac{\ln(R_0/r)}{\ln(R_0/R_+)},\\ &b)\;\; P_c<P_+<P_0,\quad \psi(r)=\Phi_+-\frac{(\Phi_+-\Phi_{ci})}{\ln(R_+/R_c)}\times\ln(R_+/r).\end{aligned}$$

Here P_0 is the initial formation pressure; P_c is the bottom hole pressure; P_+ is the saturation pressure; R_0, R_c, R_+ - the corresponding radii at P_0, P_c, P_+; A_k is the coefficient of permeability change; η_k - coefficient of irreversible change of the permeability; K is the absolute permeability; S_1 is a coefficient equal to the mass of the gas dissolving in a unit of volume when the pressure is increased by 0.1 MPa; ρ_o (P)- the density of oil; μ_o, μ_Γ - accordingly viscosity of oil and gas; F_o (S,P), $F_g(S,P)$ - phase permeability for oil and gas; M is the porosity of the formation; S is the saturation; R is the gas constant; T is the absolute temperature; $Z(P)$ is the gas supercompressibility coefficient; P - current pressure; R is the radius.

The first term in square brackets on the left-hand side of the second equation (1.1) determines the mass velocity of the gas in the free state, and the second term is the mass velocity of the gas dissolved in the liquid.

At a pressure P equal to or greater than a certain pressure P_+, all gas in the pore space is dissolved in the liquid, i.e. For P $P+$ we can write the following relations: $S=1$, $F_r=0$, $W_r=0$.

Suppose that for $P\geq P+$ the equality $S_1(P)=s+lP$ holds. This means that at any pressures above $P+$, the mass $S+$ of the gas dissolved in a unit volume of the liquid remains constant. With this definition of the functions $S_1(P)$, equation (1.1) remains valid for all values of P.

The second equation of system (1.1) can be represented as follows:

$$\frac{1}{r}\frac{d}{dr}\left\{\frac{K(P,a_k)F_o(S,P)\rho_o(P)}{\mu_o(P)}\times\times\left[\frac{PF(S,P)\mu_o(P)}{\rho_o(P)\mu_\Gamma(P)F_o(S,P)RTZ(P)}+\frac{PS_1(P)}{\rho_o(P)}\right]r\frac{dP}{dr}\right\}=0, \tag{1.2}$$

where $K=K_0[1+a_k(P-P_0)]$.

Integrating equation (1.2) and comparing with Darcy's law, we obtain:

$$\frac{K(P,a_k)F_H(S,P)\rho_o(P)}{\mu_o(P)}r\frac{dP}{dr}=\frac{G_o}{2\pi h}$$

$$\frac{K(P,a_k)F_o(S,P)\rho_o(P)}{\mu_o(P)}\times$$
$$\times\left[\frac{PF(S,P)\mu_o(P)}{\rho_o(P)\mu_\Gamma(P)F_o(S,P)RTZ(P)}+\frac{PS_1(P)}{\rho_o(P)}\right]r\frac{dP}{dr}=\frac{G_\Gamma}{2\pi h}. \tag{1.3}$$

From the expression for the gas factor F, which is equal to the ratio of the second equation of system (1.3) to the first, it is easy to obtain the relation between pressure and saturation for the steady motion of a gassed liquid:

$$F=\frac{PS_1(P)}{\rho_o(P)}+\frac{PF(S,P)\mu_o(P)}{\rho_o(P)F_o(S,P)\mu_\Gamma(P)RTZ(P)}. \tag{1.4}$$

This means that the value of the gas factor is constant along the streamline. As can be seen from (1.4), the elastoplastic properties of the formation do not affect the value of the gas factor. If, by any closed curve bounding the region under consideration, the quantity P does not change, then $\Gamma = const$.

We note that equation (1.3) can be written as follows:

$$\rho_o(P)W_o=\frac{K_+\rho_o(P)F_o(S,P)}{\mu_o(P)}\left[1+a_k(P-P_0)\right]r\frac{dP}{dr}, \tag{1.5}$$

where $K_+ = K_0[1 + a_k(P_+ - P_0)],\ P \le P_+$.

Then for the magnitude of the inflow of fluid mass to the well, we have:

$$G=\frac{2\pi hK_+}{\ln(R_+/R_c)}\int_{P_c}^{P_+}\frac{\rho_o(P)\left[1+a_k(P-P_0)\right]F_o(S,P)dP}{\mu_o(P)}, \tag{1.6}$$

Where K_+ is the permeability of the formation at a pressure P_+. The values of $\rho_o(P)$ and $\mu_o(P)$ are determined from the data of laboratory studies of [21].

As it is known, the oil structure changes when the reservoir pressure decreases below the initial pressure, that resulting in a decrease in oil viscosity and density. This occurs before the saturation pressure is reached, at which the separation of the dissolved gas from the oil begins. When the pressure drops below the saturation pressure, the viscosity and density of the oil increase due to its degassing.

We introduce the function:

$$\Phi=\int\frac{\rho_o(P)F_o(S,P)\left[1+a_k(P-P_0)\right]dP}{\mu_o(P)}+C, \tag{1.7}$$

Analogous to the well-known function of Hristianovich (1941).
Then equation (1.6) takes the form:

$$G=\frac{2\pi hK_+\rho_0(\Phi_+-\Phi_C)}{\mu_0\ln(R_+/R_C)} \tag{1.8}$$

The function $\Phi(P)$ can be determined from the indicator lines provided that the reservoir is operated at a pressure above the saturation pressure and at bottom hole pressures below the saturation pressure, i.e. when the gas factor is constant. In the present paper, the integral (1.7) is calculated by a numerical method. The results of the calculation are shown in Fig. 4 as a function of $\Delta\Phi = f(\Delta P)$ for different values of a_k.

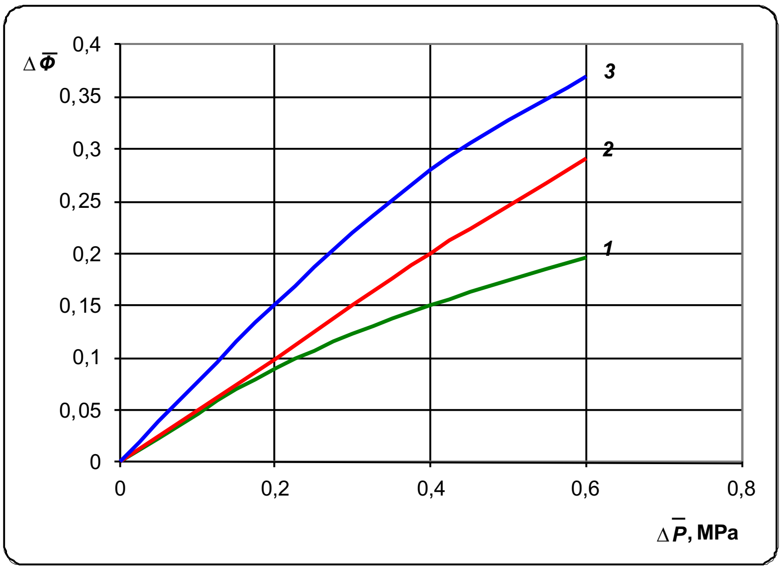

Fig. 4 Dependencies of the $\Delta\Phi$ function on the change in P for different values of the dimensionless coefficient of permeability change.

Let us consider the steady inflow of gassy fluid to the well at $P_k > P+ > P_c$.

In this case, the entire flow can be divided into two regions: the region of motion of the single-phase liquid from the external reservoir boundary $(r = R_k, P = P_k)$ to the line where the formation pressure equals the saturation pressure $(r = R_+, p = P_k$ and the two - from the line $(r = R_+, p = P_{-+}$ to the bottom of the well $(r = R_c, P = P_c)$. The formulas for the influx of a homogeneous liquid with the flow rate G_1 to the liquid degassing line with the flow rate G_2 to the well wall R_c are:

$$\begin{aligned} G_1 &= \frac{\pi h K_0 \rho_0 \left\{1-[1+a_k(P_+-P_0)]^2\right\}}{\mu_0 a_k \ln(R_k/R_+)}; \\ G_2 &= \frac{2\pi h \rho_0 [1+a_k(P_+-P_0)](\Phi_+-\Phi_0)}{\mu_0 \ln(R_+/R_c)}. \end{aligned} \tag{1.9}$$

Because of the continuity of the flow, $G_1 = G_2 = G$.

Then we get

$$\downarrow G = \frac{\pi h K_0 \rho_0 \left[\mu_0 a_k\right]^{-1} \left\{1 - \left[1 + a_k(P_+ - P_0)\right]^2\right\} + 2\pi h \left[1 + a_k(P_+ - P_0)\right] (\Phi_+ - \Phi_0)}{\ln(R_k/R_c)}. \tag{1.10}$$

The results of calculations using the formula (1.10) are shown in Fig. 5 - 7. Comparing the presented indicator lines, we can conclude the following. As in the case of the motion of a homogeneous fluid, and when a gaseous liquid moves in an elastic medium, the indicator line remains non-linear, but the productivity coefficient will be smaller than in the case of the motion of a homogeneous fluid. This fact indicates that the motion resistance of the gassy fluid increases.

The plastic filtration regime of a gassy fluid is described by the following differential equations:

$$\begin{aligned} \uparrow G_1 &= -\frac{2\pi h K_0 \rho_0}{\mu_0} \sqrt{A + B \ln r} \cdot r \frac{dP}{dr}; \\ \uparrow G_2 &= -\frac{2\pi h K_0 F_H(S,P) \rho(P)}{\mu(P)} \sqrt{A + B \ln r} \cdot r \frac{dP}{dr}. \end{aligned} \tag{1.11}$$

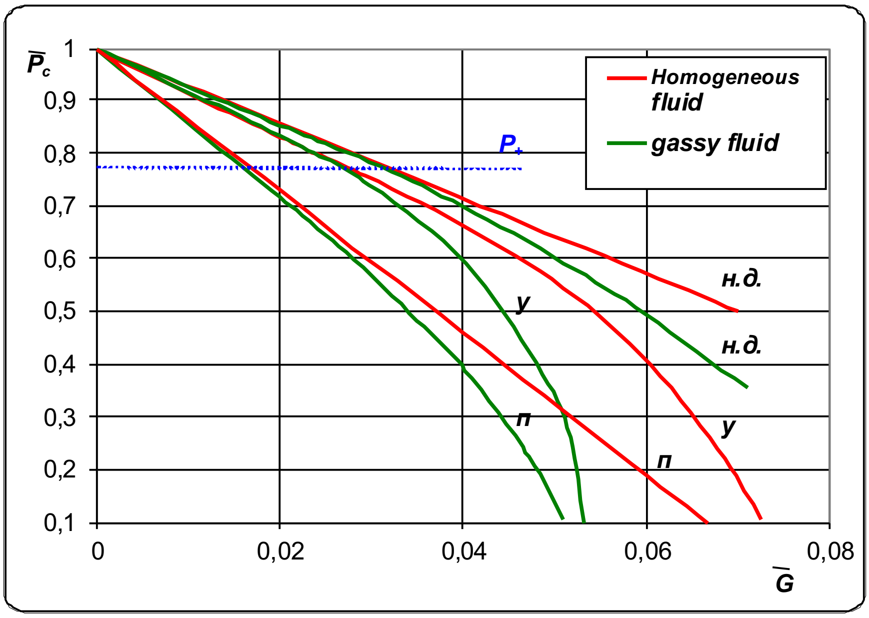

Fig. 5 Indicator lines obtained under the homogeneous and gassy fluid flow under non-deformable, elastic and plastic modes: $a_k = 1; j_k = (1 - P_i) - 1$**.**

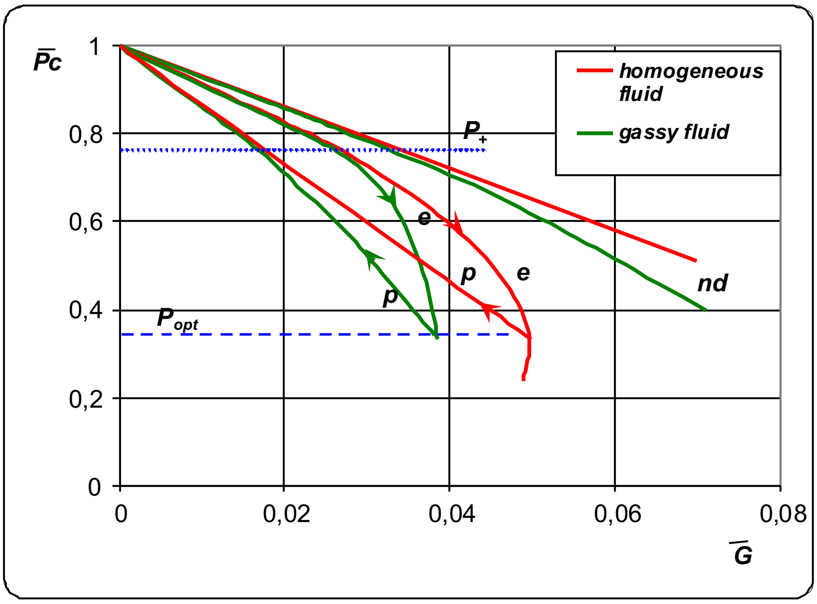

Fig.6. Indicator lines obtained under the homogeneous and gassy fluid flow under non-deformable, elastic and plastic modes: $a_k = 1.5; P_{opt} = 0.333; P_+ = 0.75$**.**

The first equation of system (1.11) describes the process of motion of a homogeneous fluid, and the second equation is the motion of a gassy fluid.

Here

a) $P_+ < P_c < P_k$

$A = 1 - B \ln R_0 \qquad B = \frac{1-[1+a_k(P_{ki}-P_0)]^2}{\ln(R_0/R_+)}$

b) $P_c < P_+ < P_k$
$A_1 = \Phi_+ - B_1 \ln R_+ \qquad B_1 = \frac{\Phi_+ - \Phi_{ci}}{\ln(R_+/R_c)}$

A similar mathematical model for describing the motion of a homogeneous fluid in a plastic medium was proposed earlier.

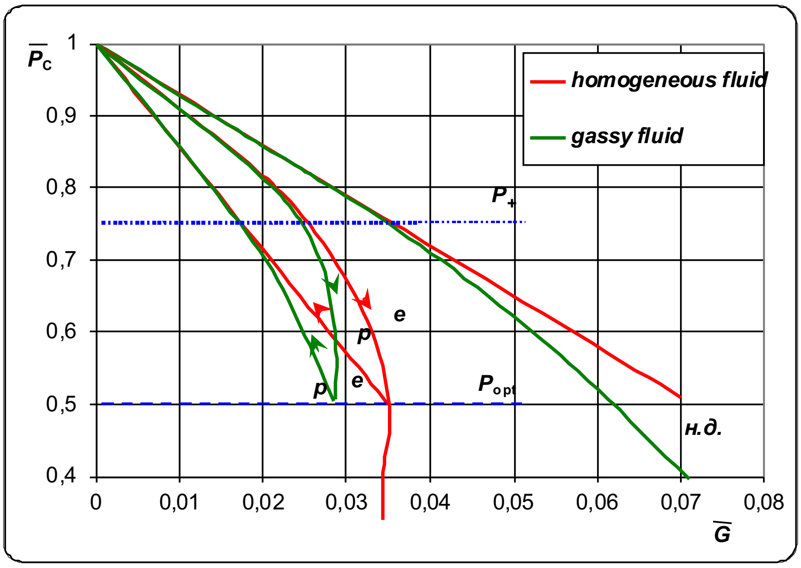

Fig. 7 Indicator lines obtained under the homogeneous and gassy fluid flow under non-deformable, elastic and plastic modes: $a_k = 2; P_{opt} = 0.5; P_+ = 0.75$.

After integrating Eq. (1.11), we obtain the formulas for determining well production rates under the plastic filtration regime for a gassed liquid:

$$\text{under } P_+ < P_c < P_0, \quad G_1 = K_1(P_0 - P_+)$$
$$K_1 = \frac{2\pi h \rho_0 K'}{\mu_0 \ln(R_k/R_+)}; \qquad K' = \frac{\{1 - [1 + a_k(P_{+i} - P_0)]^2\}}{2a_{k0}(P_{+i} - P_0)}; \tag{1.12}$$

$$\text{under } \quad P_c < P_+ < P_0, \quad G_2 = K_2(\Phi_+ - \Phi_c)$$
$$K_2 = \frac{2\pi h K''}{\ln(R_+/R_c)}\ ; \qquad K'' = \frac{\Phi_+ - \Phi_{ci}}{\sqrt{\Phi_+} - \sqrt{\Phi_{ci}}}.$$

Due to the continuity of the flow, it is possible to obtain a general formula for the inflow of gassy fluid to the well. For $G_1 = G_2 = G$

$$\uparrow G = \frac{2\pi h \rho \mu^{-1} K'(P_0 - P_+) + 2\pi h K''(\Phi_+ - \Phi_c)}{\ln(R_k/R_c)}. \tag{1.13}$$

Calculations using formulas (1.10) and (1.13) were carried out with the following additional dimensionless quantities:

$$\bar{P}_+ = \frac{P_+}{P_0}, \qquad \bar{R}_+ = \frac{R_+}{R_k}$$

And the source data:

$$\bar{P}_k = 1; \quad \bar{a}_k = 0;\ 1;\ 1,5;\ 2; \quad \bar{\eta}_k = 0; \quad -(\bar{P}_i - 1)^{-1}$$
$$\bar{P}_{ci} = 0,1;\ 0,5; \quad \bar{R}_c = 0,001; \quad \bar{F} = 1,5; \quad \bar{P}_+ = 0,75; \quad 0,065$$
$$T = 37,8^oC; \quad R = 0,082.$$

The results of calculations using formulas (1.10) and (1.13) with the indicated initial data are given in Fig. 5 - 7.

Based on calculations and graphs, it is possible to draw the appropriate conclusions and recommendations on the development of deep oil deposits under conditions of filtration of gassy fluid in a deformable medium.

From the analysis of the indicator lines of homogeneous and aerated liquids (Fig. 5 - 7), the following characteristic differences can be noted in a plastic porous medium. Despite the fact that irreversible changes in permeability occurred in the reservoir, the indicator line in the region of motion of a homogeneous liquid remains straight.

In contrast to what has been said in the region of motion of a gassy fluid, the indicator line retains its curvilinear character. This is due to the influence of two-phase flow.

The value of the optimal bottom hole pressure on the graphs does not change as in the case of the flow of a homogeneous fluid, and in the case of the motion of a gassy fluid in an elastic and elastoplastic porous medium. But at the same optimum bottom hole pressure, in the case of a homogeneous fluid motion (Fig. 5 - 7), the maximum flow rate is greater than in the case of a gassy fluid. This is due to the properties of the fluids.

In order to correctly decipher the wells data on the steady-state operating conditions, it is necessary to know the ”history” and the nature of pressure changes around the investigated well.

The mode of well operation in the plastic layer is recommended to be installed in such a way as to prevent a significant irreversible change in permeability around the working well. Therefore, reservoir pressure should be maintained at appropriate levels by various ways of influencing the formation.

2 CONCLUSIONS.

Studies have shown that with an excessive increase in the load on the formation, it is possible to reduce permeability to very low values, which is not advisable. This circumstance depends on the load (pressure drop) on the formation, the properties and composition of the rock, the depth of occurrence and other factors. In this case it is not recommended to exploit reservoirs below the optimal pressure, as this can lead to a drastic reduction or even stop filtration of the liquid through a porous medium that is under heavy load. It is precisely the large pressure drops in plastic deformable porous media that lead to the above-mentioned negative phenomena.

Based on calculations and constructed graphs, it is possible to draw conclusions and recommendations on the development of deep oil deposits represented by elastoplastic reservoirs.

When constructing the graph of the dependence $\Delta\Phi = f(\Delta P)$ (see Fig. 4), a comparison was made with similar graphs of [2]. In these papers, we compare the dependences $\Delta\Phi = f(\Delta P)$for ideal gassy and real gassy fluid.

From Fig. 4 the effect of the coefficient of permeability change on the Hristianovich function is evident, and this allows one to take into account the influence of elastic and plastic properties of rocks on the rate of production in a closed radial deposit with a gassy fluid. Attention is also drawn to indicator lines that describe the movement of real gassy oil in a real porous medium. The analysis of the graphs shows that taking into account the real properties of the formation [16, 17] as well as taking into account the real properties of the fluids, is absolutely necessary.

For the first time, the solution of the problem of the steady inflow of gassy fluid to a borehole in reservoirs with plastic rocks was obtained. This kind of deformation has almost any reservoir rocks in the development of deep oil and gas deposits, as well as sands containing a significant amount of clay cement in the development of deposits that are practically at any depth. The obtained universal dependences agree well and are explained by laboratory experiments. The obtained dependences can be used in interpreting the results of wells and reservoirs research and in determining the development indices of deposits with elastoplastic deformable reservoirs, as well as in drawing up project documents and solutions of engineering problems.

References

1. Benallal, A., Botta, A.S., Venturini, W.S.: *Consolidation of elastic–plastic saturated porous media by the boundary element method* Comput. Methods Appl. Mech. Engrg. **197**, 4626–4644 (2008).
2. Barenblatt, G.I., Zheltov, Yu.P., Kochina, I.N.: *Ob osnovnyih predstavleniyah teorii filtratsii odnorodnyih zhidkostey v treschinovatyih porodah* // PMM. **24** (5), 852–864 (1960).
3. Loret, B., Rizzi, E.: *Strain localization in unsaturated anisotropic elastic-plastic porous media with double porosity* // Journal of the Mechanics and Physics of Solids. 503–530 (1999).
4. Ju, B.: *Mathematical model and numerical simulation of multiphase-flow in permeable rocks considering diverse deformation.* Journal of Petroleum Science and Engineering **119**, 149–155 (2014).
5. Chaboche, J.L.: *A review of some plasticity and viscoplasticity constitutive theories*, Int. J. Plast., **24** (10), 1642–1693 (2008), doi:10.1016 / j.ijplas. 2008.03.009.
6. Farrell, N.J., Healy, C.D., Taylor, C.W.: *Anisotropy of permeability in faulted porous sandstones*, J. Struct. Geol. **63**, 50–67 (2014).
7. Fortin, J., Schubnel, A., Gueguen, Y.: *Elastic wave velocities and permeability evolution during compaction of Bleurswiller sandstone*, Int. J. Rock Mech. Min. Sci. **42**, 873–899 (2005).
8. Fortin, J., Gueguen, Y., Schubnel, A.: *Effects of pore collapse and grain crushing on ultrasonic velocities and* $V - p/V - s$, J. Geophys. Res., **112** (B8) (2007), doi:10.1029/2005JB004005.
9. Gorbunov, A.T., Shahverdiev, A.H.: *Issledovanie filtratsii realnoy gazirovannoy nefti uprugoplasticheskoy deformiruemoy srede*, Sb. nauch.tr. VNII, vyip.68, 106–115 (1979) (in Russian).
10. Hristianovich, S.A.: *O dvizhenii gazirovannoy zhidkosti poristyih porodah* , PMM, **5** (2) (1941) (in Russian).
11. Ma, J., Zhao, G., Khalili, N.: *A fully coupled flow deformation model for elasto-plastic damage analysis in saturated fractured porous media*, International Journal of Plasticity, **76**, 29–50 (2016).
12. Khalili, N.: *Two-phase fluid flow through fractured porous media with deformable matrix Water resources research*, **44**, W00C04, (2008). doi:10.1029/2007wr006555.
13. Kolditz, O., Bauer, S., Böttcher, N., Elsworth, D., Görke, U.J., McDermott, C.I., Park, C.H., Singh, A.K., Taron, J., Wang, W.: *Numerical simulation of two-phase flow in deformable porous media*, Application to carbon dioxide storage in the subsurface Mathematics and Computers in Simulation. **82**, 1919–1935 (2012).
14. Shahverdiev, A.H.: *Opredelenie parametrov plastov pri uprugoplasticheskom rezhime filtracii*, Izv. AN AzSSR. **4**, 93–102 (1979).
15. Shahverdiev, A.H.: *Raschet debita zhidkosti vo vremeni do proryva i posle nego v krugovuyu galereyu pri uprugom i plasticheskom rezhimah filtracii*, Izv. AN AzSSR. **1**, 53–61 (1984).
16. Shakhverdiev, A.Kh.: Sistemnaya optimizatsiya protsessov razrabotki neftyanyih mestorozhdeniy. *M.: Nedra*, 452 p. (2004).

17. Shakhverdiev, A.Kh., Panahov, G.M., Abbasov, E.M.: *Synergetic phenomena in systemic bed stimulation by thermo-rheochemical technologies*, Oil Industry Journal, Moscow, **11**, 61–65 (2002).
18. Valliappan, S., Khalili-Naghadeh, N.: *Flow through fractured porous media with deformable matrix*, Int. J. Numer. Method. Eng. Sci., **29**, 1079–1094 (1990).
19. Wang, H., W.G., Chen, Z., Wong Ron, C.K.: *Deformational characteristics of rock in low permeable reservoir and their effect on permeability*, J. Pet. Sci. Eng. **75**, 240–243 (2010).
20. Yarushina, V.M., Podladchikov, Y.Y.: *(De)compaction of porous viscoelastoplastic media: Model formulation*, J. Geophys. Res. Solid Earth, **120**, 4146–4170 (2015), doi:10.1002/2014JB011258.
21. Zinovyeva, L.A. *Analiz vliyaniya nekotoryih realnyih svoystv plastovoy nefti na protsess ee filtratsii v usloviyah rezhima rastvorennogo gaza*, Voprosyi gidrodinamiki neftyanogo plasta, Tr. VNII, Vip. VI, M., 240–253 (1954).