Seepage of a gas condensate mixture when using the geoloosening method$^{☆}$

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ABSTRACT

The problem of the seepage of a two-phase multicomponent hydrocarbon mixture for evaluating the efficiency of the use of the geoloosening method in gas condensate deposits is considered. The geoloosening method is a technology for increasing the productivity of wells, developed at the Institute of Problems in Mechanics of the Russian Academy of Sciences, and it ensures an increase in the permeability of the critical zone of a well because of directed relief of the stratum. The initiation of the geoloosening process requires the creation of deep depressions at the well bottom and, as a result, there is an accumulation of retrograde condensate in the neighbourhood of the well, which leads to a decrease in the phase permeability with respect to the gas. It is necessary to take account of the existence of these two processes, which are mutually counter directed from the point of view of the change in permeability, when this method is used for gas condensate deposits. Due to the change in the chemical composition of the mixture in the condensation process and the action of capillary forces, the gas content at each point and each instant is not the equilibrium content and, consequently, cannot be directly determined from the phase diagram of the substance. A differential scheme is used to describe the seepage of the mixture, according to which, unlike an integral scheme, the relation for the transition into the liquid phase is specified for increments and not for the pressure and volume values themselves. Numerical calculations of the steady seepage of a hydrocarbon mixture are carried out for the necessary depression levels for the conditions in the Astrakhan gas condensate deposit and the effectiveness of the use of the geoloosening method there is demonstrated.

It is well known that a deterioration in the seepage properties of the stratum rock even in a small neighbourhood of a well considerably reduces its productivity. A reduction in the permeability in the critical zone of a well (CZW) occurs during boring as a result of the ingress of the boring solution into the stratum (silt deposition) and, during the exploitation of the well, as a result of contamination (silting up, paraffinication, etc.) of the seepage channels, especially in the neighbourhood of the well. The current methods used for the treating the CZW with the aim of restoring its natural permeability (vibrational action, pulsed hydraulic action, cyclic interchange of short-lived depressions and repressions, etc.) are mainly directed towards "decontaminating" the existing seepage channels by removing extraneous particles, but these methods often do not produce the desired effect.

A new approach to the problem of increasing the productivity of oil and gas wells and enhancing the oil and gas yield from the strata has been developed in the Institute of Problems in Mechanics of the Russian Academy of Sciences. It is based on the proposition that problems concerning the deformation and breakdown of the soil skeleton of the collectors of petroleum and gas deposits and the effect of these processes on the seepage properties of the strata are the basic problems from the point of view of increasing the output from wells.[1] On the basis of this approach, a new method is proposed for increasing the productivity of petroleum wells, namely, the geoloosening methods, which increases the permeability of the CZW due to directed relief of the stratum.[2] It involves the creation of a depression of a certain level at the well bottom in conjunction with the preliminary execcution of certain technological operations: perforations of the necessary type and density and the cutting of orientated slots. As a result, there is cracking and disintegration of the rock in the neighbourhood of the well and a new system of seepage channels is formed, the permeability of which far exceeds the natural permeability of the rock. The determination of the level of the depression and the technological operations necessary to initiate the geoloosening process are achieved by testing the rock on a unique test bench with independent tri-axial loading at the Institute of Problems in Mechanics and carrying out the corresponding calculations.

The use of the geoloosening method in gas condensate wells has a number of important features. In the first place, it is associated with the phenomenon of so-called retrograde condensation, which involves separating out of the liquid phase (condensate) in zones of the well where the pressure drops below a certain critical value (the condensation pressure). The initiation of the geoloosening process, which is directed towards increasing the absolute permeability of the layer, requires the creation of deep depressions at the well bottom, as a result of which there is an accumulation of retrograde condensate in the CZW which leads to a decrease in the phase permeability of the collector with respect to the gas. It is necessary to take account of the existence of these two processes, which are mutually conuter-directed from the point of view of the change in permeability, when using this method in the case of gas condensate deposits.

The process of two-phase seepage of a multicomponent hydrocarbon mixutre allowing for the deformation and disintegration of the rock in the near vicinity of the well in the case of a change in the stress state is investigated below.

1. Integral and differential multiphase multicomponent seepage schemes

One of the key phenomena which complicate the overall picture of the seepage of multiphase multicomponent mixtures is retrograde condensation. This phenomenon is common to an extremely wide class of multicomponent fluids.[3] Acording to current ideas, any model of multiphase multicomponent mixtures must include the following equations:

equations of continuity: these can either be written for each component of each phase or for a group of components (in the limiting case, it is possible to consider a single group containing all the components). Mass exchange between the phases is taken into account; equations, describing the seepage laws for each phase; here, the flow parameters can depend on the component composition of the phases and, moreover, taking account of the relative phase permeabilities is a key factor here.
equations governing a change in the phase states.

In the mathematical modelling of multicomponent mixtures, the most widely used methods are based on the use of the Starling-Carnahan and Peng-Robinson equations of state[4] which ensure a uniform accuracy of the calculation in the being investigated region both with respect to the equilibrium composition as well as the properties of the coexisting phases. Modifications of the three-constant equation of state, proposed by Brusilovskii,[5,6] are used in the high-temperature and high-pressure region. The explicit or implicit assumption of the possibility of treating the seepage process as an equilibrium process, that is, assuming that, at each instant and at each spatial point, the state of the mixture can be treated accurately as a thermodynamically equilibrium state, is an extremely important factor in the above-mentioned schemes. Furthermore, it is assumed that this equilibrium, or quasi-equilibrium, state is independent of the type and structure of the rock space and that its parameters can be determined in laboratory experiments.

A fundamentally different approach to the design of a model of multiphase, multicomponent seepage has been proposed in[7], which is distinguished by the type of relations used to determine a change in the phase states (the third group of equations in the classification given above). The proposed model[7] is based on the assumption that a phase transition occurs according to the phase diagram in each portion of the gas when the pressure is changed. In this case, by virtue of the capillary connections between the liquid phase and the skeleton and the finiteness of the rate of mixing of the components in the liquid phase, the relative content of the phases at each point and at each instant is not the equilibrium content and, consequently, it cannot be directly determined from the phase diagram of the substance, but can only be found by direct integration of the differential equations obtained. This approach can be called the differential approach (since the phase equilibrium condition is written for a portion of the mixture which has entered, that is, for an increment, unlike in the classical integral approach). The implicit assumption that a substance, on once transferring into the liquid phase, remains in this state is also important. The physical basis of this assumption is the existence of capillary forces binding the liquid phase particles. It should be noted that the assumption regarding the possibility of a reverse phase transition occurring according to the same laws immediately leads to a reversion to the integral scheme considered above, with simple integration of the differential relations considered. In practice, such a differential scheme has not been widely used for multicomponent seepage calculations.

Of the two schemes mentioned, the differential scheme must lead to higher values of the relative liquid phase concentrations and, consequently, to lower values of the inflows compared with the integral scheme. In reality, the seepage process occurs according to laws to which the schemes considered are approximations. The use of any one of the schemes and the acquisition with its help of results agreeing with experiments is possible, since this is always done in practice by introducing empirical correction coefficients.

An estimate of the effectiveness of the use of the geoloosening method for gas condensate deposits using the differential approach is presented below.

2. Estimate of the effectiveness of the geoloosening method in gas condensate deposits

The seepage of a two-phase mixture can be described by a system of differential seepage equations for each phase, taking account of mass transfer between the phases. The equations of continuity for each of the phases are written in the following form

$$m\frac{\partial}{\partial t}[\rho_g \sigma] + \text{div}[\rho_g \mathbf{v}_g] + Q = 0, \quad m\frac{\partial}{\partial t}[\rho_f(1-\sigma)] + \text{div}[\rho_f \mathbf{v}_f] - Q = 0 \tag{2.1}$$

Here m is the porosity, ρ is the density, υ is the seepage rate, Q is the mass of the gas transferring into the liquid phase per unit volume of the porous medium per unit time and σ is the relative content of the gas phase. Quantities, referring to the gas phase, are indicated by a subscript g and those referring to the liquid phase are denoted by a subscript f. All the processes are assumed to occur isothermally on account of the large heat capacity of the skeleton of the layer.

The motion of each of the phases is assumed to be an inertialess motion which obeys Darcy's law

$$\mathbf{v}_g = -\frac{k}{\mu_g}f_g(\sigma)\text{grad}\,p, \quad \mathbf{v}_f = -\frac{k}{\mu_f}f_f(\sigma)\text{grad}\,p \tag{2.2}$$
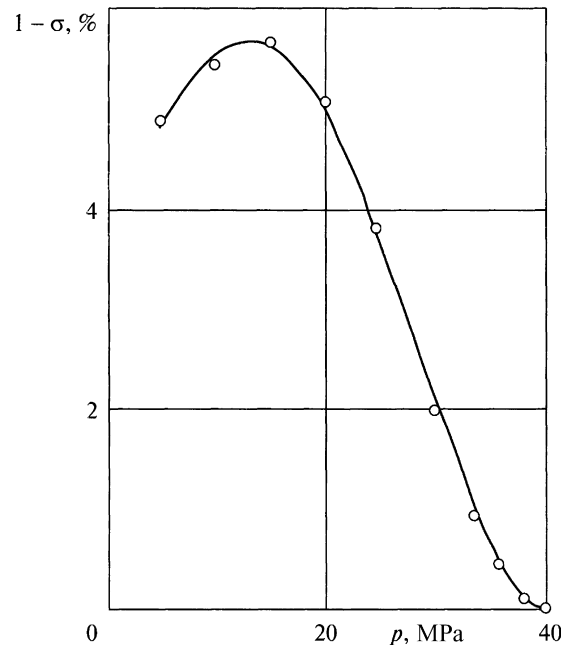
Fig. 1.

Here p is the pressure, k is the permeability of the porous medium, μ is the dynamic viscosity and $f(\sigma)$ are the relative phase permeabilities.

If it is assumed that, at each instant and at each point in space, the relative content of the gas σ in the gas condensate mixture corresponds to the equilibrium content and is determined exclusively by the current pressure p (the temperature is assumed to be constant), then σ can be assumed to be a specified function of the pressure. The curve of the dependence $\sigma(p)$ (the condensation isotherm) for the conditions of the Astrakhan gas condensate deposit (AGCD) is shown in Fig. 1. Addition of Eq. (2.1) enables us to eliminate the quantity Q and, when account is taken of Eq. (2.2), we obtain a single differential equation in the pressure p

$$m\frac{\partial}{\partial t}[\rho_g\sigma] + m\frac{\partial}{\partial t}[\rho_f(1-\sigma)] - \operatorname{div}\left[\rho_g\frac{k}{\mu_g}f_g(\sigma)\operatorname{grad} p\right] - \operatorname{div}\left[\rho_f\frac{k}{\mu_f}f_f(\sigma)\operatorname{grad} p\right] = 0$$

(2.3)

However, as has already been mentioned above, the existence in the composition of a gas condensate mixture of several hydrocarbon fractions with dissimilar physico-chemical properties makes it considerably more difficult to describe the seepage process. This is associated with the character of the phase diagrams of multicomponent mixtures which are fundamentally different from the phase diagrams of pure substances and depend on the chemical composition of the mixture.[8] Among these differences are the following.

1. The presence of two-dimensional regions in the pressure - temperature phase diagrams corresponding to the conditions for the simultaneous existence of a liquid and a gaseous phase.
2. The presence of retrograde regions where condensation and evaporation occur in a direction which is opposite to the phase transitions of the pure substance. Retrograde condensation means that the amount of liquid formed increases when the pressure is reduced from the pressure at the beginning of condensation to the pressure of maximum condensation at the given temperature.
3. A change in the chemical composition of each of the phases during phase changes, since, the heavy C_{5+} fractions preferentially condense when the pressure is reduced below the start of condensation at the given temperature.

After the passage of seepage stratal gas through a point of the layer with a pressure below the pressure for the onset of condensation in the porous medium, the heavier fractions precipitate out in the form of condensate. As a result of capillary forces, the liquid which has separated out can be immobilized or it seeps at a rate which is less than the rate of the seeping gas. An accumulation of the retrograde condensate, predominantly consisting of the heavy C_{5+} fractions, occurs in the porous medium. In this way, the chemical composition of the mixture at the points of the layer considered changes during the seepage, and the ratio of the liquid and gas phases does not correspond to the equilibrium ratio for the initial composition of the stratal gas and cannot be determined from the condensation isotherm obtained from experiments in a closed vessel.

The assumption that, in each portion of gas which is subjected to a pressure change, there is a phase transition in accordance with the phase diagram of the stratal gas is natural. In other words, the relation for the transition for each portion of gas into the liquid phase when the pressure is changed, i.e.,

$$dV = \Phi(p)dp$$

(2.4)

holds. Here, V is the volume of the gas transferring into the liquid phase and $\Phi(p)$ is a function of the pressure, which can be obtained as the derivative of $\sigma(p)$ determined by the condensation isotherm, that is, unlike in the integral scheme, the relation is specified for increments rather than for the quantities themselves.

The mass of gas per unit volume of the medium is $\rho_g \sigma m$ and, for the quantity Q, we obtain

$$Q = \rho_g \sigma m \frac{dV}{dt} = \rho_g \sigma m \Phi(p) \frac{dp}{dt} \tag{2.5}$$

In the case of a moving medium, the total derivative of the pressure with respect to time for the gas particles is

$$\frac{dp}{dt} = \frac{\partial p}{\partial t} + \mathbf{w}_g \operatorname{grad} p, \quad \mathbf{w}_g = \frac{\mathbf{v}_g}{m\sigma} \tag{2.6}$$

where w_g is the velocity of motion of gas particles in the pores. Substitution of expression (2.6) into equality (2.5) and then into the first equation of (2.1) in succession, taking account of the first expression of (2.2), gives the equation

$$m\frac{\partial}{\partial t}[\rho_g \sigma] - \operatorname{div}\left[\rho_g \frac{k}{\mu_g} f_g(\sigma)\operatorname{grad} p\right] + \rho_g \Phi(p)\left[\sigma m\frac{\partial p}{\partial t} - \frac{k}{\mu_g} f_g(\sigma)(\operatorname{grad} p)^2\right] = 0 \tag{2.7}$$

which, together with Eq. (2.3), gives a system of two equations in the two unknowns p and σ.

The problem of the seepage of gas in a well can be considered in the first approximation as an axi symmetric problem and, in this case, Eqs (2.3) and (2.7) are transformed to the following form

$$m\frac{\partial}{\partial t}[\rho_g \sigma] + m\frac{\partial}{\partial t}[\rho_f(1-\sigma)] - \frac{1}{r}\frac{\partial}{\partial r}\left[r\rho_g \frac{k}{\mu_g} f_g(\sigma)\frac{\partial p}{\partial r}\right] - \frac{1}{r}\frac{\partial}{\partial r}\left[r\rho_f \frac{k}{\mu_f} f_f(\sigma)\frac{\partial p}{\partial r}\right] = 0$$

$$m\frac{\partial}{\partial t}[\rho_g \sigma] - \frac{1}{r}\frac{\partial}{\partial r}\left[r\rho_g \frac{k}{\mu_g} f_g(\sigma)\frac{\partial p}{\partial r}\right] + \rho_g \Phi(p)\left[\sigma m\frac{\partial p}{\partial t} - \frac{k}{\mu_g} f_g(\sigma)\left(\frac{\partial p}{\partial r}\right)^2\right] = 0 \tag{2.8}$$

where r is a polar coordinate.

To estimate of the effectiveness of the operation of a well, the steady seepage performance is of interest. In the case of a steady flow, the system of partial differential equations (2.8) is transformed into the system of ordinary differential equations

$$\frac{d}{dr}\left[r\rho_g \frac{k}{\mu_g} f_g(\sigma)\frac{dp}{dr}\right] + \frac{d}{dr}\left[r\rho_f \frac{k}{\mu_f} f_f(\sigma)\frac{dp}{dr}\right] = 0$$

$$\frac{1}{r}\frac{d}{dr}\left[r\rho_g \frac{k}{\mu_g} f_g(\sigma)\frac{dp}{dr}\right] + \rho_g \Phi(p)\frac{k}{\mu_g} f_g(\sigma)\left(\frac{dp}{dr}\right)^2 = 0 \tag{2.9}$$

A number of relations appear in this system which characterize the properties of the stratal fluid of a specific deposit and are determined experimentally:

the dependence of the ratio of the liquid and gaseous phases in the mixture on the pressure (the condensation isotherm),
the phase permeabilities as a function of the ratio of the phases,
the dependence of the density of the gas and condensate on the pressure,
the dependence of the dynamic viscosity of the gas and condensate on the pressure at the temperature in the stratum.

The experimentally found dependences of the condensate saturation $1 - \sigma$, the phase permeabilities f_g and f_f, the phase densities ρ_g and ρ_f, and the viscosities μ_g and μ_f, made available by VNIIGAZ, as well as the curves of the smoothing functions approximating these relations for the conditions in the AGCD which had been chosen for carrying out these calculations, are shown in Figs. 1–4 (the dimension of pressure is MPa, the dimension of density is ton/m^3 and the dimension of viscosity is mPa.s).

$$\Phi(p) = 0.01(0.0692 + 0.00357(40 - p) - 0.0000456(40 - p)^2)$$

$$\rho_g = 0.03383p - 0.00022p^2, \quad \rho_f = 0.794 + 2.85/\sqrt{p}$$

$$\mu_g = 0.174 + 0.0206p, \quad \mu_f = 34.5 + 903/p$$

$$f_g = \frac{1}{120(1-\sigma)^4 + 3.26(1-\sigma)^2 + 1}, \quad f_f = 0.64(1-\sigma)^4 + 0.01(1-\sigma) \tag{2.10}$$

The experimental data are shown by the points, and the curves represent the approximating functions. The solid points and solid curves in Figs. 2–4 correspond to quantities for the condensate, and the open circles and the dashed lines correspond to quantities for the gas.

The model must also take into account the change in the seepage properties of a rock as a function of the stress state in the near vicinity of the well and the deformation and disintegration of the soil skeleton associated with it.

There are actually two possibilities to obtain a change in the stresses acting in the critical zone of a well: controlling the pressure on the well bottom and creating the necessary structure of the well bottom. When the depression in the well is increased, the shear stresses in its neighbourhood, responsible for fracturing, become larger. In the case of a vertical uncased well, there is a redistribution of the stresses in which the stresses acting in a radial direction are reduced by the magnitude of the depression, the circumferential stresses increase and the stresses acting in a vertical direction remain at roughly the same level (the Lamé problem). The circumferential stresses finally reach a level at which fracturing of the rock occurs (cracking and disintegration), accompanied by a sharp increase in its permeability. The
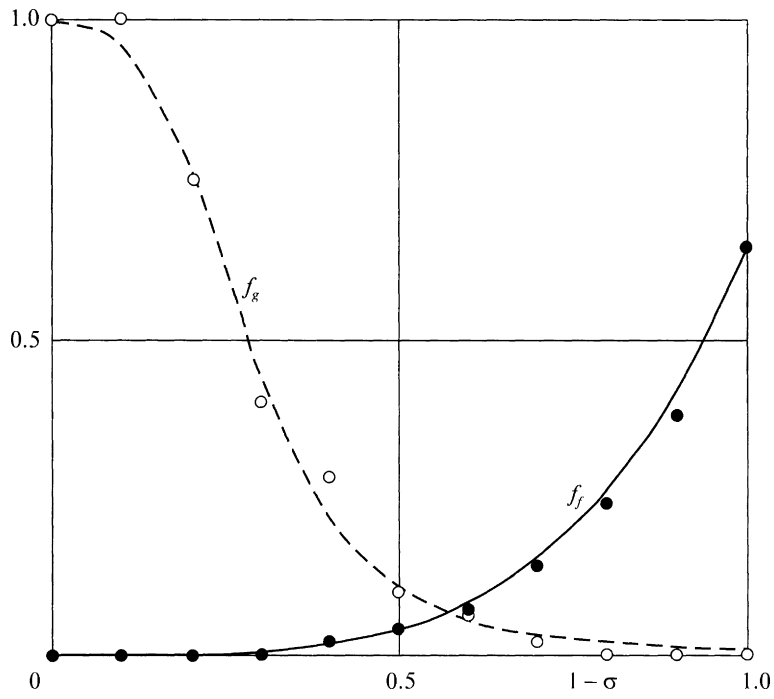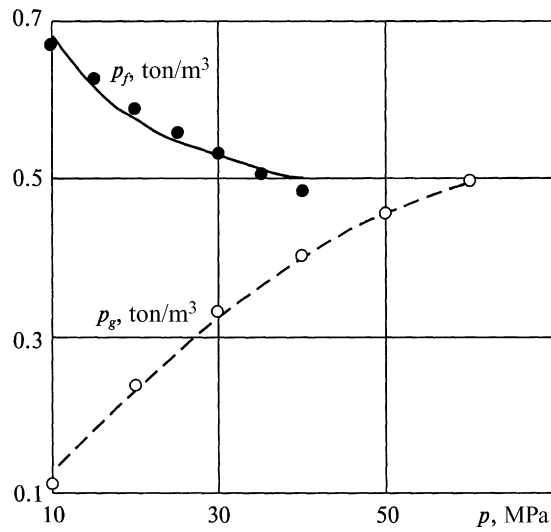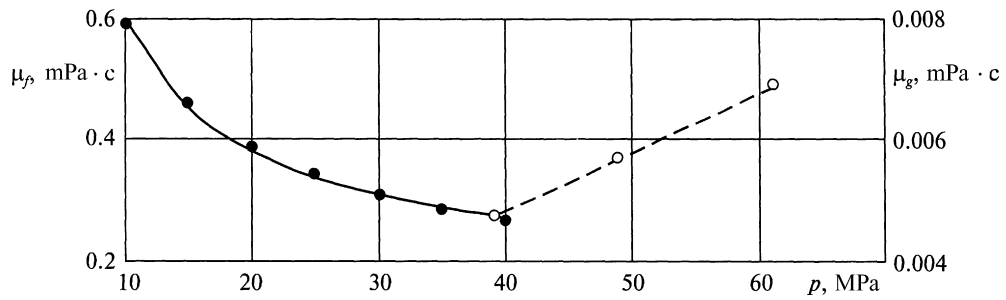
Fig. 2.

Fig. 3.

Fig. 4.

magnitude of the depression at which fracturing occurs is determined by testing samples of the collector rock from a specific deposit on a test bench. Tests were carried out on samples of rocks from the collector of the AGSD. Samples in the form of a cube with an edge length of 50 mm were prepared. The stress state, which arises in the neighbourhood of the open shaft of the well and in the vicinity of the perforation holes when the depression at the well bottom hole is increased, was created in them using the test rig. The change in the permeability in a radial direction during the loading process was recorded. The experiments enabled us to determine that, when a depression of 35–40 MPa is produced the rock is inelastically deformed and there is a sharp irreversible increase in its permeability. So, before the work using the geoloosening method is carried out in the neighbourhood of the well, there is a silt deposition zone of radius r_1 with a permeability k_1 which is several times less than the natural permeability of the collector k_0 and, in this case, the permeability of the stratum will be

$$k = k(r) = \begin{cases} k_1, & r_c \leq r \leq r_1 \\ k_0, & r_1 \leq r \leq r_k \end{cases}$$

where $r_k = 100\, r_c$ is the radius of the feed contour.

Data from geophysical investigations show that the size of this zone is usually 3–5 times the well radius r_c.[8] Calculations were carried out for three values of the radius of the silt deposition zone $r_1/r_c = 3, 4, 5$.

After the work is carried out, that is, after the creation of a deep depression, a zone of increased permeability k_2 with a radius r_2 is formed around the well. The radius of the loosered zone r_2 depends on the magnitude of the depression: the greater the depression, the deeper this zone extends into the stratum.

If $r_2 \geq r_1$, then

$$k = k(r) = \begin{cases} k_2, & r_c \leq r \leq r_2 \\ k_0, & r_2 \leq r \leq r_k \end{cases}$$

The smooth approximating function

$$k'(r) = 1 + \frac{k_2' - 1}{2}[1 - \mathrm{th}\beta(r' - r_2')]; \quad k' = \frac{k}{k_0}, \quad r' = \frac{r}{r_c} \tag{2.11}$$

was used in the calculations. Here β is a coefficient which takes account of the sharpness of the change in the permeability on passing from the critical zone deep into the layer; its value has a weak effect on the results. In the calculations, it was assumed that $\beta = 6$.

If $r_2 \leq r_1$, then

$$k = k(r) = \begin{cases} k_2, & r_c \leq r \leq r_2 \\ k_1, & r_2 \leq r \leq r_1 \\ k_0, & r_1 \leq r \leq r_k \end{cases}$$

and the approximating function has the form

$$k'(r) = 1 + \frac{k_2' - k_1'}{2}[1 - \mathrm{th}\beta(r' - r_2')] + \frac{k_1' - 1}{2}[1 - \mathrm{th}\beta(r' - r_1')] \tag{2.12}$$

Calculations of the steady seepage of the stratal fluid were carried out for the conditions in the AGCD and a pressure at the well bottom hole of corrresponding to the operational depression value of 20 MPa, before and after the work was done using the geoloosening method. Correspondingly, the boundary conditions were as follows:

$p(r_k) = 60$ MPa is the layer pressure in the AGCD,
$p(r_c) = 40$ MPa is the operational pressure at the well bottom.

3. Calculation algorithm

The problem was partly solved by integrating the differential equations and, where this could not be done analytically, it is done numerically using the MATHEMATICA program. Before carrying out the work using the geoloosening method, single phase seepage took place at a well bottom hole pressure of 40 MPa. It can be seen from Fig. 1 that the pressure of the condensate p_K for the stratal conditions in the AGCD is 40 MPa, because condensate does not form in the layer at a well bottom hole pressure of 40 MPa. In this case, the first equation of (2.9) takes the form

$$\frac{d}{dr}\left[r\rho_g(p)\frac{k(r)}{\mu_g(p)}\frac{dp}{dr}\right] = 0 \tag{3.1}$$

After substituting the second and fourth expressions of (2.10) and expression (2.11) into it, Eq. (3.1) is easily integrated by separation of the variables:

$$\int_{p(r_c)}^{p(r_k)} \frac{\rho_g(p)}{\mu_g(p)}\, dp = \int_{r}^{r_k} \frac{C_1}{rk(r)}\, dr \tag{3.2}$$

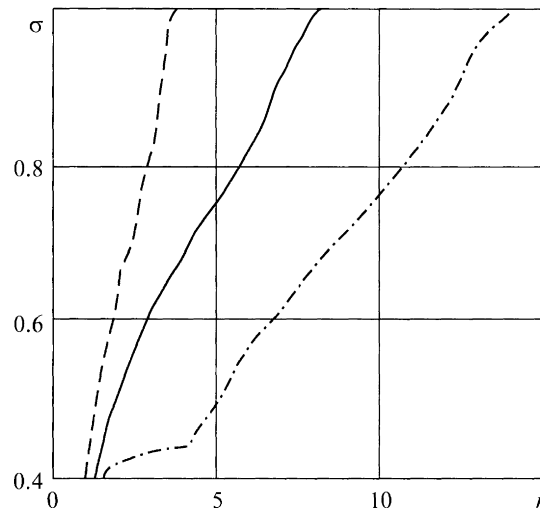Here, the constant C_1 is found from the condition $p(r_c) = 40$ MPa.

Fig. 5.

The seepage, after carrying out the work using the geoloosening method, is also calculated by solving Eq. (3.1) but with a different dependence of the permeability on the coordinate which has to be computed. It has already been mentioned above that the geoloosening technology involves the creation of a deep depression at the well bottom hole of a well which is sufficient to crack the rock in the critical zone. At the same time, condensate is formed in a certain neighbourhood of the well where the pressure drops below p_k. In order to determine the condensate saturation distribution in the stratum formed under deep depression, the system of equations (2.7) was solved, taking account of expressions (2.10) - (2.12), with the boundary conditions

$$p(r_k) = 60 \text{ MPa}, \quad p(r_c) = 20 \text{ MPa}$$

The following algorithm was used. In order to determine the condensate saturation at the instant of the termination of the work, the region considered was divided into two parts: an external part $r_* < r < r_k$ and an internal part $r_c < r < r_*$, the boundary between which r_* corresponds to the pressure at the start of retrograde condensate precipitation and must be determined from the solution of the problem. A zeroth approximation to the value of the seepage rate in the feed contour $\upsilon_g(r_k)$ was then specified for which a value of r_*, which satisfies Eq. (3.1), was sought in the external region. Here, the constant C_1 was found from the condition $p(r_*) = 40$ MPa. The value of the seepage rate corresponding to the Dupuis solution was chosen as the zeroth approximation. After this, the system of equations (2.9) for the internal problem was solved with the boundary conditions

$$p(r_*) = 40 \text{ MPa}, \quad \frac{k(r_*)}{\mu_g(p_*)} \frac{dp(r)}{dr}\bigg|_{r=r_*} = -\upsilon_g, \quad \sigma(r_*) = 1$$

and the pressure on the wall of the well $p(r_c)$ was found. In the case when this pressure does not match the limit value $p(r_c) = 20$, the next approximation was made for the seepage rate in the feed contour $\upsilon_f(r_k)$ by means of a change with a given step size (1% of the preceding approximation) and the procedure was repeated.

Curves of the gas saturation distribution in the steady state for a well bottom hole pressure of 20 MPa are shown in Fig. 5. The solid line is for a homogeneous stratum. The dashed line is for a stratum with a critical zone, which has deteriorated by a factor of 10 as a result of silt deposition and the dot-dash line is for a stratum which has been improved by a factor of 10 as the result of geoloosening of the critical zone.

No new condensate is formed when the well bottom hole pressure is raised to the operational value of 40 MPa and the precipitated condensate now flows out into the well. It can be seen from Fig. 2 that, in the case of a condensate saturation of less then 0.3, the phase permeability of the condensate practically vanishes and it is immobile. In the part around the wall of the well where the condensate saturation exceeds a value of 0.3, the condensate saturation value drops to a value of 0.3 preserving at a steady state and seepage into the well is occuring. In the region, where the condensate saturation is less than 0.3 and the condensate does not seep, its value does not change. The final calculation for the steady state after the work using the geoloosening method has been done, is carried out using the solution of Eq. (3.1), replacing $k(r)$ by $k(r)f_g(\sigma(r))$. The solution has the form

$$\int_{p(r_c)}^{p(r_k)} \frac{\rho_g(p)}{\mu_g(p)} \, dp = \int_r^{r_k} \frac{C_2}{rk(r) f_g(\sigma(r))} \, dr \tag{3.3}$$

Here, the constant C_2 was found from the condition $p(r_c) = 40$ MPa.

Curves for the gas permeability distribution when $p(r_c) = 40$ MPa are shown in Fig. 6 for two cases: when there is a zone in the neighbourhood of the well with an absolute permeability reduced by a factor of 10 ($r_1 = 4$) due to silt deposition (the dashed line) and when there is a zone in the neighbourhood of the well with a permeability ($z_2 = 4$) which has been enhanced by a factor of 10 due to the work carried out using the geoloosening method (the dot-dash line). In the second case, there is a region with a size of the order of 17 radii in the neighbourhood of the well where condensate has precipitated out, which approximately holves the gas permeability with respect to the natural permeability.
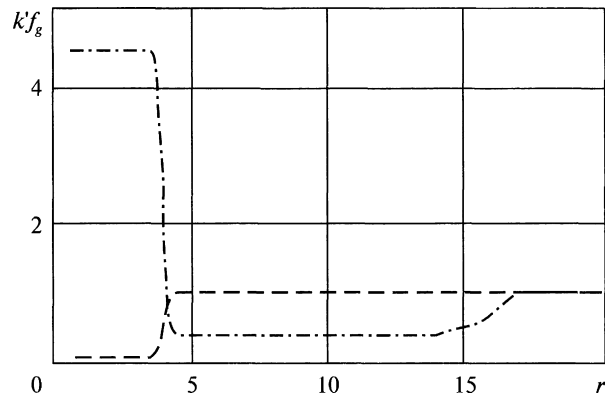
Fig. 6.

Table 1

Condition of the CZW	Size of the CZW		
	$r_1' = 3$	$r_1' = 4$	$r_1' = 5$
a) before carrying out work according to geoloosening method			
$k_1' = 0.1$	0.33	0.27	0.25
b) after carrying out work according to geoloosening method			
$k_2' = 5$	$r_2' = r_1'$		
	0.71	0.77	0.82
	$r_2' = 3$		
	0.71	0.47	0.31
$k_2' = 10$	$r_2' = r_1'$		
	0.74	0.80	0.87
	$r_2' = 3$		
	0.74	0.50	0.33

Gas output values for steady conditions for different values of the absolute permeability in the well bottom zone, before and after carrying out the work using the geoloosening method, are shown in Table 1. Here, Q' is the output from the well, divided by the output in a stratum with a homogeneous permeability k_0. Calculations were carried out for three values of the sitted zone and three values of the loosened zone: 3, 4 and 5 radii of the well in different combinations. A comparison of these values shows that the creation of strong depressions and the retrograde condensation associated with them worsens the operational characteristics of a well in comparred with an ideal well even when there is a geoloosening zone. However, in the case of a real well with an impaired well bottom zone, the geoloosening method provides a noticeable effect. How strongly the permeability increases as a result of geoloosening is not of great significance. It is important that the loosened zone should be greater or identical in size with the silt deposition zone, that is, that no poorly permeated zone remains around the well. Otherwise, the effect of geoloosening is negligible.

It should be noted that a temporary depression is required for the creation of a zone with an improved permeability in the neighbourhood of the well and, in this case, the condensate does not succeed in accumulating in those volumes which are formed in the event of arriving at a steady state and the gas permeability falls to a smaller extent than the calculations predict. Moreover, the formation of a new developed system of cracks as a result of geoloosening must lead to a change in the phase permeability curves, and the existence of condensate will retard the gas motion to a lesser extent. Thus, the estimate obtained gives a lower limit of the effectiveness of the use of geoloosening for the Astrakhan gas condensate deposit.

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