

IRREVERSIBILITY OF GAS-CONDENSATE FLOW IN GAS CYCLING PROJECTS: KINETICALLY STABLE SATURATION PATTERNS

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IRRÉVERSIBILITÉ DES ÉCOULEMENTS DE GAZ
À CONDENSAT DANS LES PROJETS DE RECYCLAGE
DE GAZ : PROFILS STATIONNAIRES DE SATURATION

Cet article présente une étude de la dynamique d'un réservoir biphasique multiconstituant approchant le régime d'écoulement stationnaire. En premier lieu, nous procédons à une approximation linéaire du modèle compositionnel dans le cas des petites fluctuations autour du régime permanent. Une expression analytique est ainsi obtenue pour le temps caractéristique de transition. Des simulations numériques sont ensuite effectuées pour les déviations importantes par rapport au régime permanent. Nous avons ainsi pu étudier le déplacement linéaire d'un mélange gaz/condensat par un gaz enrichi suivi d'un régime de production. On montre alors que le changement de composition des phases et de pression lors de l'évolution vers l'état d'équilibre évolue selon un temps caractéristique comparable à la durée d'injection. Cependant, le changement de saturation et de composition globale est environ 200 fois plus long que la durée d'injection. En conséquence, l'ensemble du réservoir montre une distribution de saturation non homogène dans l'espace, pendant un temps anormalement long. Des comportements stationnaires du même type ont également été découverts dans d'autres systèmes dynamiques non linéaires : transitions de phase, plasmas, films minces. Nous avons examiné la question de l'existence de régimes permanents discontinus pour ce type d'écoulement multiconstituant. Il n'existe en fait aucune solution de ce type dans le cas d'un mélange binaire¹.

IRREVERSIBILITY OF GAS-CONDENSATE FLOW
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SATURATION PATTERNS

The dynamics of a two-phase multicomponent reservoir system which is approaching the steady-state flow regime are studied. First, the compositional model is analyzed in the linear approximation, for the case of a small initial deviation from the steady-state regime. An analytical expression is obtained for the characteristic relaxation time. Next, numerical simulations are

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(1) After Mitlin V.S. (1993) Nonlinear Dynamics of Reservoir Mixtures, CRC Press, Boca, Raton.

performed for situations where there is a substantial deviation from the steady-state regime. The linear injection of an enriched gas into a gas-condensate reservoir, followed by the extraction regime, is simulated. It is shown that the change in phase compositions and pressure on the way to equilibrium proceeds with characteristic times of the order of the injection time. However, the change in the saturation and overall composition takes approximately 200 times longer than the injection time. Thus, the reservoir system manifests a spatially inhomogeneous saturation distribution for an abnormally long time. Similar kinetically stable patterns have been also discovered in the nonlinear dynamics of phase transitions, plasma, and thin films. The question of the existence of discontinuous steady states for this multicomponent flow is considered. In the case of a binary mixture, it is shown that such solutions do not exist¹.

CIRCULACIONES DE GAS-CONDENSADO
EN LOS PROYECTOS DE RECIRCULACIÓN DE GAS :
PERFILES DE SATURACIÓN CINÉTICAMENTE
ESTABLES

Se ha procedido al estudio de la dinámica de un yacimiento bifásico multicomponentes en situaciones cercanas del régimen de circulación estacionaria. En primer lugar, se procede al análisis del modelo composicional, por aproximación lineal al tratarse de las pequeñas fluctuaciones en torno del régimen permanente. Se obtiene de tal modo una expresión analítica para el tiempo característico de transición. A continuación, se emprenden simulaciones numéricas para los desvíos importantes con respecto al régimen permanente. Se estudia de tal modo el desplazamiento lineal de una mezcla gas/condensado por un gas enriquecido seguido de un régimen de extracción. Se demuestra que la modificación de la composición de fases y de la presión durante la evolución tendiente hacia el estado de equilibrio evoluciona a su vez según un tiempo característico de la misma magnitud que el tiempo de inyección. La modificación de saturación y de composición global precisa un tiempo, que aproximadamente, es unas 200 veces mayor que el tiempo de inyección. Por consiguiente, el conjunto del yacimiento muestra una distribución de saturación no homogénea en el espacio, y ello durante un lapso de tiempo anormalmente dilatado. También se han descubierto en las dinámicas no lineales de las transiciones de fase, del plasma y de las películas finas, diversos modelos cinéticamente estables del mismo tipo. Se ha examinado y demostrado que no existe ninguna solución de este género en el caso de una mezcla binaria al tratarse de la existencia de regímenes permanentes discontinuos para este tipo de circulación de componentes múltiples¹.

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1 MATHEMATICAL MODEL

If capillary and gravitational forces and molecular diffusion are neglected, the system of equations for multicomponent isothermal flow through porous media can be written in the following form, presuming local equilibrium (Collins, 1990):

$$\begin{aligned} \nabla(k\beta_i \nabla P) &= \frac{\partial(\phi N z_i)}{\partial t}, \quad i = 1, \dots, n; \\ \beta_i &= \frac{k_g \rho_g y_i}{\mu_g M_g} + \frac{k_c \rho_c x_i}{\mu_c M_c}; \quad N = \frac{S \rho_c}{M_c} + \frac{(1-S) \rho_g}{M_g}; \\ z_i &= V y_i + (1-V) x_i; \quad \frac{y_i}{x_i} = K_i; \\ S &= \frac{(1-V) \rho_g M_c}{(1-V) \rho_g M_c + V \rho_c M_g}; \quad \sum_{i=1}^n \frac{(K_i - 1) z_i}{1 + V(K_i - 1)} = 0 \end{aligned} \quad (1.1)$$

Here, P is the pressure; $\rho_{g,c}$, $\mu_{g,c}$, $k_{g,c}$, and $M_{g,c}$ are the densities, viscosities, relative permeabilities, and molecular weights of the gas and liquid (condensate) phases; K_i , x_i , y_i and z_i are the equilibrium constant and the mole fractions of the i -th component in the liquid, in the gas, and in the mixture; k and ϕ are the absolute permeability and the porosity; S is the liquid saturation; N is the total molar density of the mixture; β_i is the mobility coefficient of the i -th component; and V is the mole fraction of the gas phase.

The system of Equations (1.1) probably is the most popular model to describe the dynamics of compositional reservoir flow. The literature on compositional modeling is huge (see, for example, the reviews in Aziz and Settari (1979) and Lake (1989)). In this paper the model (1.1) will be studied within the general hydrodynamic framework. Specifically, the dynamics of the parameters describing the compositional flow (i.e. the pressure, the phase compositions, the saturation, and the overall compositions) in transient processes, i.e. on the way to the steady-state flow regime, will be studied. This question is considered both for small initial deviations of these parameters from their steady-state values (which will be done analytically, in the linear approximation) and for large deviations (which requires numerical simulations). It will be demonstrated that in the case of large deviations, the dynamics can drastically differ from the predictions of the linear theory.

2 SMALL FLUCTUATIONS: THE LINEAR APPROXIMATION

First, the problem of how the system goes over into the steady-state solution, when this solution is fairly close to the spatially homogeneous solution and the initial deviation of the system from the steady-state regime is fairly small, will be studied. This can be done by linearizing the system of equations in (1.1) with reference to the spatially homogeneous solution ($P = \text{constant}$; $z_i = \text{constant}$). This linearization yields:

$$\frac{\partial P'}{\partial t} = I \nabla^2 P'; \quad \frac{\partial z_i'}{\partial t} = \frac{k}{\phi N} (\beta_i - z_i \beta) \nabla^2 P', \quad i = 1, \dots, n-1 \quad (2.1)$$

$$I = \frac{k}{\phi} \left(\frac{\partial N}{\partial P} \right)^{-1} \left[\beta - \sum_{i=1}^{n-1} \frac{1}{N} \frac{\partial N}{\partial z_i} (\beta_i - z_i \beta) \right], \quad \beta = \sum_{i=1}^n \beta_i \quad (2.2)$$

where P' and z_i' are the fluctuations relative to the spatially homogeneous solution, and β is the mobility coefficient of the two-phase mixture. The quantity I in Equations (2.1) and (2.2) is the rate of relaxation to a spatially homogeneous state. This quantity, I , was previously introduced in the literature in connection with the behavior of autowaves in two-phase compositional flow (Mitlin, 1990). It is clear from Equation (2.1) that I determines (for constant k and ϕ) the evolution of the system in the linear approximation.

For a binary mixture, the phase compositions, densities, and viscosities depend on the pressure only. Taking P and S as the independent variables, Equation (2.2) can be rewritten:

$$I = \frac{k}{\phi} \left[\beta_1 \left(\frac{\rho_c x_2}{M_1} - \frac{\rho_g y_2}{M_g} \right) - \beta_2 \left(\frac{\rho_c x_1}{M_1} - \frac{\rho_g y_1}{M_g} \right) \right] \times \left[\left(\frac{\rho_c x_2}{M_1} - \frac{\rho_g y_2}{M_g} \right) \left(S \frac{\partial}{\partial P} \left(\frac{\rho_c x_1}{M_1} \right) + (1-S) \frac{\partial}{\partial P} \left(\frac{\rho_g y_1}{M_g} \right) \right) - \left(\frac{\rho_c x_1}{M_1} - \frac{\rho_g y_1}{M_g} \right) \left(S \frac{\partial}{\partial P} \left(\frac{\rho_c x_2}{M_1} \right) + (1-S) \frac{\partial}{\partial P} \left(\frac{\rho_g y_2}{M_g} \right) \right) \right]^{-1} \quad (2.3)$$

Figure 1 shows the dependency of the quantity $I^* = \phi I/k$ on S , as determined from Equation (2.3) for various pressures. The mixture used in the calculations in Figure 1, consists of methane (75%) and *n*-hexane (25%), at 335°K. The properties of the two-phase mixture were calculated from the Peng-Robinson equation of state. The relative permeability

functions were taken to have the following form (Corey, 1986):

$$k_c = \left(\frac{S-0.36}{0.64} \right)^3, \quad k_g = \left(\frac{0.88-S}{0.88} \right)^3, \quad 0.36 < S < 0.88$$

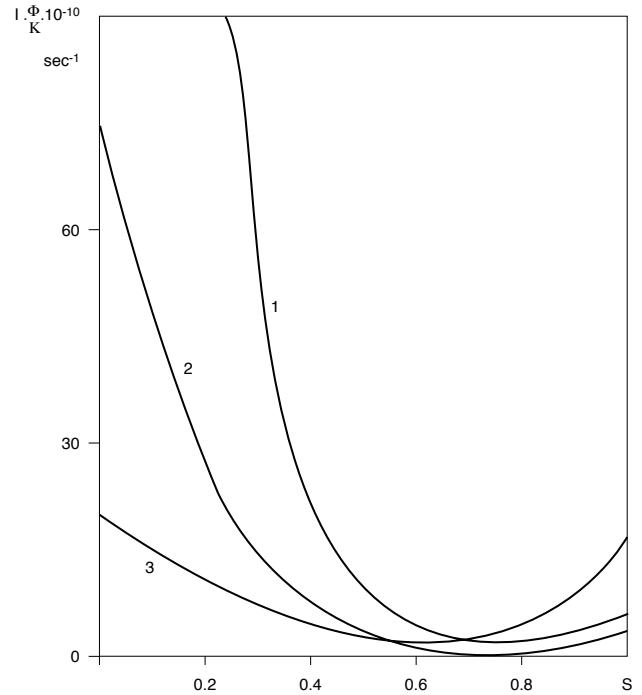


Figure 1

Dependence of the relaxation rate at the pore scale on liquid saturation S for different pressures P and a given mixture composition. 1: $P = 8$ MPa; 2: $P = 12$ MPa; 3: $P = 17$ MPa.

Curves 1 through 3 in Figure 1 are developed at pressures of $P = 8, 12$ and 17 MPa, respectively. The curves are convex downward, the minimum being reached at $S \sim 0.6-0.8$. With an increase in pressure, the relaxation rate for the pure gas decreases, while the relaxation rate for the liquid increases. This is associated with the convergence of the phase properties as the upper pressure limit of the two-phase region and hence the critical point is approached. From Figure 1, it also follows that as the pressure increases the minimum of the relaxation rate is shifted towards the left. Note that I^* corresponds to the reciprocal of the relaxation time on scales of the order of the pore channels. The evolution on scales L is determined in the linear approximation by characteristic times of the order of L^2/I .

3 NUMERICAL SIMULATION OF A GAS CYCLING TREATMENT: A NONLINEAR SLOWDOWN

If deviations from the steady-state solution are not small, the relaxation process can only be characterized by solving the nonlinear system (1.1) numerically. The results of calculating the recovery of gas-condensate mixture from one end of a two-dimensional linear reservoir after injecting an enriched gas through the same end are presented below. A compositional simulator was used to solve this problem. This simulator is described elsewhere (Mitlin, 1993).

The initial and boundary conditions are as follows:

$$\begin{aligned}
 t = 0 : P(r, 0) &= P^0, \quad z_i(r, 0) = z_i^0, \quad i = 1, \dots, n, \quad 0 < r < L \\
 t < t^* : z_i(0, t) &= \delta_i, \quad i = 1, \dots, n, \quad -\frac{k\beta}{N} \frac{\partial P}{\partial r} = v, \quad r = 0 \\
 t \geq t^* : \frac{k\beta}{N} \frac{\partial P}{\partial r} &= v, \quad N = N(\Gamma_1, \dots, \Gamma_{n-1}, P), \quad \Gamma_i = \frac{\beta_i}{\beta}, \quad r = 0 \\
 P(L, t) &= P^0, \quad z_i(L, t) = z_i^0, \quad r = L
 \end{aligned}
 \quad (3.1)$$

Here, v is the flow velocity at the inlet; the quantity t^* corresponds to the dimensionless time (representative of the number of pore volumes injected):

$$\tau = (vt)/(\phi L) = 0.75, \quad (\phi L)/v = 96\,000 \text{ s}$$

The composition of the injected gas, δ_i , was 66% methane, 10% ethane, 10% propane, and 14% butane. The other initial data are the same as those reported in Guzhov and Mitlin (1986).

Figure 2 presents saturation profiles at various times. Curve 1 corresponds to the end of injection. Curves 2 through 6 represent $\tau = 1, 2, 30, 110$ and 170 . Clearly, the process of relaxation of the S fluctuations proceeds in two stages. For $\tau = 1$ to 3, the tail of the liquid-phase bank flows towards the reservoir inlet. The saturation at the inlet then falls sharply, and at $\tau = 10$ a saturation profile with a sharp bend is formed (curve 4). The steady-state regime is reached at time $\tau = 160$.

Figure 3 shows the process characteristics as a function of $\ln(\tau+1)$. Curve 1 corresponds to $S(0, t)$, and curve 2 represents $\Delta P = P(0, t) - P(L, t)$. The evolution of pressure, as distinct from saturation, takes place during the first stage of the relaxation process. The phase compositions also reach their steady-state values over only several units of τ . The calculations described here were performed for a ten-component mixture: as an example, the dependence of the methane fraction in

the gas phase is shown by curve 3. The slow evolution of S takes place at almost steady-state pressure and phase composition distributions. The overall composition, z_i , then varies to the extent that S varies. This means that at large times of the process the multicomponent reservoir mixture effectively behaves like a quasi-binary system.

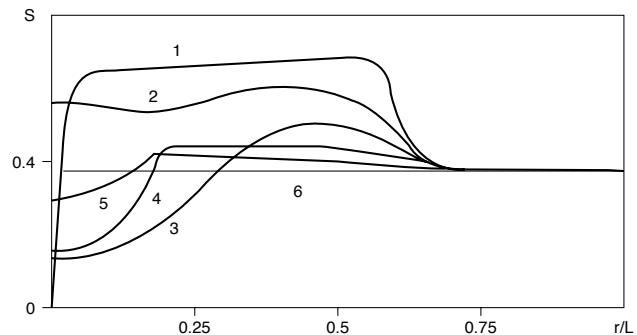


Figure 2

Dissipation of a condensate bank: evolution of the saturation profile on the way to the steady-state flow regime. 1: end of injection; 2 to 6: $\tau = 1, 2, 30, 110$ and 170 respectively.

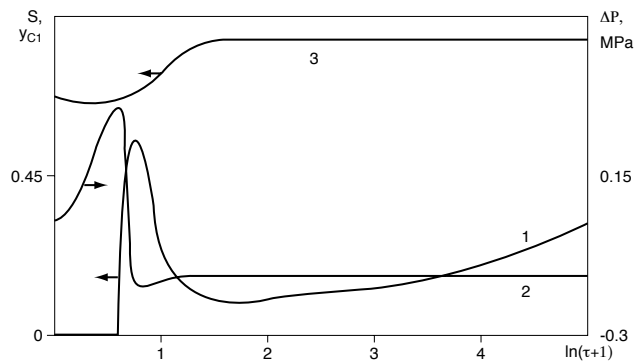


Figure 3

The dynamics of different flow parameters illustrates the presence of fast (pressure, phase composition) and slow (saturation, overall composition) variables in the system. 1: $S(0, t)$; 2: $\Delta P = P(0, t) - P(L, t)$; 3: molar fraction of methane in the gas phase.

It should be noted that an approximate solution of Equations (1.1), with the time-dependent saturation and time-independent pressure and phase compositions, has been proposed earlier by Nikolaevsky (1990). Specifically, assuming the immobility of one of the fluid phases (for instance, the liquid phase), the compositional model (1.1) can be transformed into a system of ordinary differential equations, if the phase

compositions and pressure are assumed to be time-independent. This solution was used to describe the accumulation of condensate in the near-well zone.

The binary mixture used in the previous section in calculating I , was chosen to serve as a conditional binary example of the multicomponent mixture used in the numerical simulations. Thus, the characteristic relaxation time can be determined from the linear theory (Eq. (2.3)) on the basis of the following data: $I^* = 1.5 \cdot 10^{11} \text{ s}^{-1}$, $k = 10^{-14} \text{ m}^2$, $L = 5 \text{ m}$, $\phi = 0.222$, and in order of magnitude amounts to only 1000 s. Note that the "nonlinear" relaxation time determined from numerical simulation is about four orders larger than the one determined in the linear approximation. This suggests the inapplicability of linear description in the case of large deviations from the steady-state regime.

The numerical simulations were carried out using various space and time steps. In all cases, after rapid changes in phase compositions and pressure, a subsequent slow saturation evolution was observed. This suggests that when a highly inhomogeneous space distribution of S and z_i has somehow been created in the reservoir, an accurate determination of the reservoir composition may require much larger observation times than are typically used.

4 KINETICALLY STABLE SATURATION PATTERNS

The time required for formation of the S "fluctuation" (the condensate bank) differs from its relaxation time by two orders. Such a difference in system behavior during injection and subsequent recovery regimes is associated with the irreversibility of discontinuous flow (Rozhdestvensky and Yanenko, 1978). Another noticeable fact is the formation (at $\tau = 10$) of a saturation profile with a sharp bend (curve 4 in Figure 2), followed by an extremely strong slowdown of the relaxation process. The existence of alternating stages of evolution with sharply different times on the way to the equilibrium state has also been observed in the nonlinear theory of spinodal decomposition, in the nonlinear dynamics of plasma, in the nonlinear dynamics of phase transition in dense viscous media, and in the nonlinear dynamics of dewetting (Mitlin, Manevich and Erukhimovich, 1985; Mitlin and Manevich, 1990; Mitlin and Manevich,

1992; Mitlin and Petviashvili, 1994). All of these models have some commonality. Specifically, an inhomogeneous space structure forms, as a result of evolution. Despite the fact that the structure is itself unstable, the system slows down on it for an abnormally large time. In numerical experiments, if one is unaware of the instability of the structure, one can miss the slowdown with the end of the evolution. This nonlinear phenomenon is referred to as kinetically stable structures. A comprehensive review of kinetically stable structures may be found in Mitlin (1993), Chapter 8.

5 NONEXISTENCE OF DISCONTINUOUS STEADY-STATE SOLUTIONS AND THE PROBLEM OF ESTIMATING THE RESERVES OF A GAS-CONDENSATE FIELD

A problem similar to that considered in Section 3 was solved for the plane-radial case in Mitlin (1987). However, the entire relaxation process was not traced owing to the very large computation time involved. Subject to computational constraints, the formation of a saturation profile with a sharp bend that differs from the known steady-state solution and is extremely slowly transformed suggested that the system also may have a discontinuous steady-state solution. The question of whether such discontinuous steady-state solutions exist will be considered below in more detail.

In finding a steady-state solution of the model (1.1) the overall composition (and the saturation value) of a reservoir mixture is determined by the pressure and overall composition (invariant along the streamlines) in the flow using the following relations (see, for instance, Nikolaevsky, 1990).

$$\Gamma_i^0 = \Gamma_i(z_1, \dots, z_{n-1}, P), \quad i = 1, \dots, n-1 \quad (5.1)$$

In Equation (5.1), Γ_i^0 is the composition in the flow at the boundary of the flow region; in the case of steady-state flow to a production well, this is the composition of the produced mixture. If system (5.1) can be solved for z_i , all flow characteristics are then functions of P and the steady-state flow can be determined from the Laplace equation for the flow potential function. The question is then as follows: "Is the system (5.1) always solvable for z_i and, consequently, is it possible for the steady-state solution

to be multi-valued, in which it becomes necessary to formally introduce a discontinuity?" (Whitham, 1974).

The question of whether system (5.1) can be solved is critical. The reserves of a gas-condensate field are estimated by analyzing the composition of the production stream, i.e. the quantities Γ_i^0 . If the relationship between the composition in the flow and in the reservoir is not single-valued, estimation of reserves would require additional data. The question posed can be generalized further: "What is the number of possible solutions for system (5.1), for given P and Γ_i^0 ?" For mixtures with $n > 2$, this is unknown. In particular, it is not known whether a solution to system (5.1) always exists. However, for binary mixtures, it is possible to prove single-valued solvability of system (5.1), as is shown below.

The condition for solvability is written in the form:

$$\det \begin{Bmatrix} \partial \Gamma_i \\ \partial z_j \end{Bmatrix} \neq 0 \quad (5.2)$$

Since a binary mixture can be described in terms of two independent variables, P and S , condition (5.2) can be written as:

$$\frac{\partial \Gamma_1}{\partial S} \neq 0, \quad \Gamma_1 = \frac{\frac{k_g}{k_c} \frac{\rho_g y_1}{\mu_g M_g} + \frac{\rho_c x_1}{\mu_c M_c}}{\frac{k_g}{k_c} \frac{\rho_g}{\mu_g M_g} + \frac{\rho_c}{\mu_c M_c}} \quad (5.3)$$

All the functions in Equation (5.3), except for $k_{g,c}$ depend only on P . Equation (5.3) can be rewritten in the form:

$$\frac{d}{dS} \left(\frac{k_g}{k_c} \right) (y_1 - x_1) \frac{\rho_g \rho_c}{\mu_g M_g \mu_c M_c} \neq 0 \quad (5.4)$$

For a binary mixture, in the plane "pressure-fraction of the first component", the branches of the phase diagram corresponding to the gas and liquid phases close up only at the critical point (Amyx, Bass, Whiting, 1960). Thus, in the two-phase region of the phase diagram the sign of the quantity $y_1 - x_1$ does not change, and $y_1 - x_1$ cannot vanish.

The derivative in Equation (5.4) can be expressed in the form:

$$\frac{d}{dS} \left(\frac{k_g}{k_c} \right) = \frac{\frac{dk_g}{dS} k_c - \frac{dk_c}{dS} k_g}{k_c^2} \quad (5.5)$$

For saturations corresponding to immobility of one of the phases, there are no non-trivial steady-state solutions (Nikolaevsky, 1990). If both phases are mobile, the right-hand-side of Equation (5.5) vanishes if:

$$\frac{dk_g}{dS} / \frac{dk_c}{dS} = \frac{k_g}{k_c} \quad (5.6)$$

The left-hand-side of Equation (5.6) is less than zero, and the right-hand-side is greater than zero, which is not possible. This proves the solvability of system (5.1) for a binary mixture.

DISCUSSION AND CONCLUSIONS

In this work, a popular compositional flow model has been considered. Relaxation to a steady-state flow regime was studied for a case where the initial state of the reservoir system is close to the steady state and when it is far from it. Both linear and nonlinear descriptions of the relaxation process in the reservoir system were considered. The linear description used an analytical approximation. The nonlinear analysis relied on numerical simulations. The following conclusions may be drawn from these evaluations.

For a linear description, the relaxation process can be characterized by the relaxation rate, I . For a binary mixture, the relaxation rate is a non-monotonic function of saturation, the slowest relaxation is observed at a saturation level corresponding to mobility of both phases.

For a nonlinear representation, the relaxation process is much more complex. Displacement of a gas-condensate mixture by an enriched gas, with subsequent transition to the recovery regime, was numerically evaluated. It was shown that the time required for formation of a condensate bank was two orders of magnitude smaller than the time for its dissipation.

The characteristic relaxation time determined in the linear approximation is four orders of magnitude smaller than the "nonlinear" relaxation time for a large (the condensate bank) fluctuation.

"Nonlinear" relaxation times are very different for different variables describing the system. For example, pressure and phase composition relaxation times are two orders of magnitude smaller than those for saturation and overall composition.

It is argued that the observed nonlinear slowdown of the reservoir system at a certain inhomogeneous

saturation structure, is another example of kinetically stable structures recently recognized in other branches of nonlinear science.

The problem of estimating reserves in a gas-condensate reservoir, based on production composition, was considered. It was shown that the relationship between the production composition and the reservoir composition is unambiguous, for a binary mixture. For mixtures with more components, whether this relationship is unambiguous is unknown.

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