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INTERPRETATION OF STATIONARY WELL INVESTIGATIONS FOR GAS-CONDENSATE FIELDS

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On the basis of previously obtained solutions for equations of two-phase filtration with phase transitions, we suggest and analyze methods for determining a number of hydromechanical quantities from experimental "depression–output" curves for operating wells of gas-condensate fields.

In [1-3], a method was described for solving a one-dimensional stationary problem of filtration with phase transitions for a two-phase gas-condensate mixture. The solutions obtained make it possible in principle to predict the dependences of output on depression for operating wells. Such dependences are called indicator curves. In practice they are obtained in stationary investigations of wells and are usually used for estimating the permeability of the well-bottom zones. However, it turns out that the functional form of the dependence of solutions for a filtration problem on free parameters allows one to extract a great amount of useful information from experimental indicator curves. In the present work we describe methods for calculating different hydromechanical quantities from the results of stationary investigations of wells.

Below, we will reproduce briefly the necessary information from [1-3].

Suppose there is a stationary cylindrically symmetric filtration flow of a two-phase gas-condensate type system in a uniform isotropic porous medium. A hydrocarbon liquid, i.e., a condensate, is formed on a decrease in pressure in the native gas as a result of the so-called phenomenon of retrograde condensation [4, 5]. We will assume the process to be isothermal, and, therefore, will everywhere omit its temperature dependence.

We will use the notation: r for the distance to the well axis; k for the permeability; f_{g}, p_{g}, μ_{g}, n_{g} for the relative phase permeability, pressure, shear viscosity, and for the mole gas density, respectively; f_{liq}, p_{liq}, μ_{liq}, and n_{liq} for the similar quantities for the condensate. Moreover, assume that $c_{i\mathrm{g}}$ and $c_{i\mathrm{liq}}$ are the mole concentrations of the components in the gas and condensate, with the subscript i running from 1 to N, where N is the total number of components. The filtration region is determined by the inequalities

$$r_{\mathrm{w}} \le r \le r_0 , \tag{1}$$

where r_{w} is the borehole radius along the drill bit; r_0 is the radius of the supply contour. The following boundary conditions hold:

$$p_{\mathrm{g}}|_{r=r_{\mathrm{w}}} = p_{\mathrm{w}}, \quad p_{\mathrm{g}}|_{r=r_0} = p_0 , \tag{2}$$

where p_{w} is the pressure at the bottom of the well; p_0 is the pressure in the bed, $p_{\mathrm{w}} \le p_0$. For gas-condensate fields in a bed (i.e., far from the borehole) the fluid is either in the gas phase or in a two-phase state in which the liquid phase (condensate) occupies an insignificant pore volume and can be considered motionless. Let c_{i0} be the composition of the movable (gas) phase of the native fluid, and p_{d} be the pressure of the onset of condensation corresponding to this composition. By virtue of the assumptions made, the following inequality holds

$$p_{\mathrm{d}} \le p_0 . \tag{3}$$

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Within the region of filtration (1) the compositions of the gas and condensate are interrelated as

$$Wc_{i\text{liq}} + (1 - W)\, c_{ig} = c_{i0} \,. \tag{4}$$

Here W is a nonnegative function of pressures p_g and p_{liq} in the phases. If we interpret the quantity W as the mole fraction of the liquid phase in contact condensation of a mixture with composition c_{i0}, then the dependence $W = W(p_g, p_{\text{liq}})$ can be found from laboratory experiments or from calculations from semiempirical equations of state [5, 6].

In the problem considered the filtration relationships lead to a set of equations:

$$f_g \frac{dp_g}{d\xi} = (1 - W)\, \mu_g n_g^{-1}\,, \quad f_{\text{liq}} \frac{dp_{\text{liq}}}{d\xi} = W \mu_{\text{liq}} n_{\text{liq}}^{-1}\,, \quad p_g - p_{\text{liq}} = p_c \,. \tag{5}$$

Here we use the parameter $\xi = Q(2\pi kh)^{-1}\ln(r/a)$, where Q is the output of the well in moles per time; h is the thickness of the permeable layer; a is the arbitrary positive quantity with the dimension of length. We consider the phase permeabilities and capillary pressure jump p_c as functions of the saturation s of the pore space by the liquid phase. Let, in addition, the following functional dependences be known:

$$p_g = p\,(n_g, c_{ig})\,, \quad p_{\text{liq}} = p\,(n_{\text{liq}}, c_{i\text{liq}})\,, \quad \mu_g = \mu\,(n_g, c_{ig})\,, \quad \mu_{\text{liq}} = \mu\,(n_{\text{liq}}, c_{i\text{liq}})\,. \tag{6}$$

Then the system of equations (5) can be considered a closed problem for determining the functions $p_g = p_g(\xi)$, $p_{\text{liq}} = p_{\text{liq}}(\xi)$, and $s = s(\xi)$. Really, the values of W, c_{ig}, and $c_{i\text{liq}}$ are defined as functions of p_g and p_{liq} from relations (4). The subsequent substitution into Eq. (6) also makes it possible to express n_g, n_{liq}, μ_g, and μ_{liq} as functions of p_g and p_{liq}. Let s_* be the mobility threshold for the liquid phase. If $s_* = 0$, then a solution of system (5) is unique with accuracy to the shift in the parameter ξ [3]. If $s_* > 0$, we specify the solution by the additional condition $s = 0$, when $W = 0$.

Suppose there is a certain solution for system (5):

$$p_{g0}\,(\xi)\,, \quad p_{\text{liq}0}\,(\xi)\,, \quad s_0\,(\xi)\,. \tag{7}$$

It is easy to construct a solution of the filtration problem that would satisfy boundary conditions (2). In fact, since $p_{g0}(\xi)$ is a monotonically increasing function (see the first equation in system (5)), there are single values of ξ_w, ξ_0 ($\xi_w < \xi_0$) for which

$$p_{g0}\,(\xi_w) = p_w\,, \quad p_{g0}\,(\xi_0) = p_0 \,.$$

The output is calculated by the formula

$$Q = 2\pi kh\,(\xi_0 - \xi_w)/\ln\,(r_0/r_w)\,. \tag{8}$$

After this, it is easy to find the spatial distribution of pressures and saturation:

$$p_g = p_{g0}\,(\xi_0 + \Delta\xi)\,, \quad p_{\text{liq}} = p_{\text{liq}0}\,(\xi_0 + \Delta\xi)\,, \quad s = s_0\,(\xi_0 + \Delta\xi)\,,$$
$$\Delta\xi = Q\,(2\pi kh)\,\ln\,(r/r_0)\,. \tag{9}$$

Taking as a basis the presented properties of the exact solutions for the filtration problem, we will consider the possible approaches to the interpretation of the experimental depression–output indicator curve:

$$Q = F\,(\Delta p)\,, \quad \Delta p = p_0 - p_w \,. \tag{10}$$

In subsequent Sections 1-4 we assume that relation (10) is known for a certain operating well.

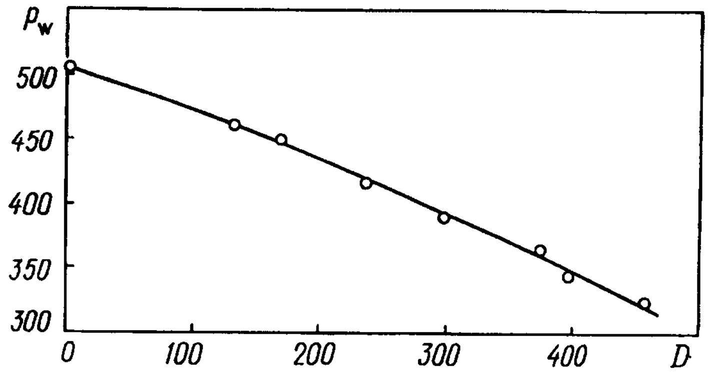

Fig. 1. Dependence of well-bottom pressure on output (curve, theory; points, experiment). p_w, atm; D, m^3/day.

1. Determination of the Mean Permeability. In practice, inflow to a well arrives not from one layer, but from a system of layers with thicknesses h_m and permeabilities k_m ($m = 1, ..., M$), where the values of h_m can be considered known. Moreover, suppose we know a certain solution of Eq. (7) either in analytical form [1, 3] or as a result of numerical calculation. We assume that except for the thickness and permability, all the remaining characteristics of the layers coincide. For the prescribed value of p_w, we find the inflow from each layer from formula (8). Summing up and substituting relation (10), we obtain

$$F(\Delta p) = \bar{k} F_* (\Delta p) , \tag{11}$$

$$F_* (\Delta p) = 2\pi \bar{h} (\xi_0 - \xi_w)/\ln (r_0/r_w) , \quad \bar{h} = \sum_{m=1}^{M} h_m ,$$

$$\bar{k} = \bar{h}^{-1} \sum_{m=1}^{M} h_m k_m .$$

Relation (11) represents a redefined system of equations for finding the mean permeability $\bar{k}$ over the well section. For actual situations an exact proportionality between the experimental curve $F(\Delta p)$ and theoretical curve $F_*(\Delta p)$ is of low probability, because of measurement errors and inaccurate information about the properties of the mixture and phase permeabilities. Therefore, the value of $\bar{k}$ should be determined from the condition of the least difference between the right- and left-hand sides of Eq. (11), for example, by the least-squares method.

As an example illustrating the application of this technique, we present the results of processing the data on stationary investigations of well No. 10-P in the Karachaganakskii pertoleum-gas-condensate field (the Republic of Kazakhstan) within the range of 3932-3971 m. The corresponding experimental data are presented in Fig. 1. The theoretical curve ensures the least quadratic deviation at the mean permeability value $k = 7.3 \cdot 10^{-15}$ m^2. The approximation, used in practice, by the dependence on the output in the form of a quadratic trinomial [6] gives in this case the value $k = 9.2 \cdot 10^{-15}$ m^2.

2. Prediction of the Well Output. Suppose we know the values of the total discovered thickness $\bar{h}$ and mean permeability $\bar{k}$ for a well. It is required to find the curve $F'(\Delta p)$, Eq. (10), for a certain other well with known thickness $\bar{h}'$, mean permeability $\bar{k}'$, drainage radius r_0', and local native pressure p_0'. For the composition of the mobile phase of the bed mixture to be the same we will assume, in accordance with Eq. (3), that the following inequalities are satisfied:

$$p_d \le p_0' \le p_0 . \tag{12}$$

From formula (11) we find

$$F'(\Delta p) = \kappa F(\Delta p), \quad \kappa = \bar{k}'\bar{h}' \ln(r_0/r_w)/(\bar{k}\bar{h}\ln(r_0'/r_w)).$$

3. Reconstructing the Solution of the Filtration Problem. It is required to find the spatial distribution of pressure in the gas phase in filtration through a permeable layer that has drainage radius r_0' and local native pressure p_0'. As before, we will assume that inequalities (12) are satisfied. We will use $\Delta p = G(Q)$ to denote the dependence inverse to Eq. (10). Then we fix a certain value of the bottom pressure of the well p_w. Let Q_0 and Q_0' be the outputs that correspond, according to Eq. (10), to pressures p_w and p_0' at the well bottom. Using formula (9), we find that

$$p_g = p_0 - G(q), \tag{13}$$

$$q = (Q_0 - Q_0') \ln(r_0'/r)/\ln(r_0'/r_w) + Q_0'.$$

Expression (13) gives a partial solution of the filtration problem. It should be noted that the result is independent of the filtration characteristics of the layer in the vicinity of the initial well.

4. Determination of the Absolute and Phase Permeabilities. Let the capillary pressure jump be equal to zero. In this case the pressures in the gas and liquid phases coincide. We use the notation $\varphi_g = \bar{k}f_g$ for the mean phase gas permeability and $\varphi_{liq} = \bar{k}f_{liq}$ for the mean phase condensate permeability. System (5) can be converted to the form:

$$(f_g n_g \mu_g^{-1} + f_{liq} n_{liq} \mu_{liq}^{-1}) \frac{dp}{d\xi} = 1, \tag{14}$$

$$W f_g n_g \mu_g^{-1} - (1 - W) f_{liq} n_{liq} \mu_{liq}^{-1} = 0. \tag{15}$$

Now we will consider formula (11). We will assume that the quantities p_w and ξ_w are variable and denote $\Phi = \Phi(p_w) = dF/d\Delta p$. Differentiating both parts of formula (11), we obtain

$$\Phi \frac{dp_w}{d\xi_w} = \frac{2\pi\bar{k}\bar{h}}{\ln(r_0/r_w)}.$$

From this expression and from Eqs. (14)-(15), making the identifications $p_w \to p$ and $\xi_w \to \xi$, we obtain two relations

$$\varphi_g n_g \mu_g^{-1} + \varphi_{liq} n_{liq} \mu_{liq}^{-1} = \Phi_* = \Phi \ln(r_0/r_w)(2\pi\bar{h})^{-1},$$

$$W\varphi_g n_g \mu_g^{-1} - (1 - W)\varphi_{liq} n_{liq} \mu_{liq}^{-1} = 0,$$

from which we can find expressions for the total phase permeabilities as functions of the pressure $p \le p_0$ at the corresponding point of the filtration flow:

$$\varphi_g = (1 - W)\mu_g n_g^{-1} \Phi_*, \quad \varphi_{liq} = W \mu_{liq} n_{liq}^{-1} \Phi_*. \tag{16}$$

Since the value of saturation s at a given pressure remains unknown, then, generally speaking, relations (16) are insufficient to find the phase permeabilities φ_g and φ_{liq} as saturation functions for determining the absolute permeability $\bar{k}$. Nevertheless, Eq. (16) makes it possible to obtain certain restrictions on the values sought.

Thus, we will introduce the variable $\Delta\varphi = \varphi_{liq} - \varphi_g$, which should be a strictly monotonic function of saturation s. Eliminating the pressure from expressions (16), we can find the nondecreasing function

$$\varphi_{liq} = \varphi_{liq}(\Delta\varphi). \tag{17}$$

The expressions used in calculations for phase permeabilities (for lithotypes of a given deposit) must be consistent with experimental curve (17).

Then, if there is a rigorous inequality $p_d < p_0$, or if a mobility threshold for the condensate is absent, i.e., $s_* = 0$, then the mean absolute permeability can be determined from functions (16) as the maximum value of the total phase permeability for the gas:

$$\bar{k} = \varphi_{g\,max}, \quad \varphi_{g\,max} = \max\left\{\varphi(p) \,|\, p \le p_0\right\}.$$

Otherwise, there is a lower bound:

$$\bar{k} \ge \varphi_{g\,max}.$$

Thus, knowledge of the theoretically obtained exact solutions for the problem of the filtration of a gas-condensate mixture and the experimental indicator curves makes it possible to calculate a number of important hydromechanical values. Moreover, in order to obtain useful information, it is often sufficient to use a functional form of the dependence of the solution on the free parameters without resorting to an explicit form of solution.

NOTATION

r, distance to the well axis; r_w, radius of the well along the drill bit; r_0, r_0', drainage radii; k, k_m, permeability values; $\bar{k}$, $\bar{k}'$, mean permeability; h, h_m, values of layer thicknesses; $\bar{h}$, $\bar{h}'$, total thickness of permeable layers; M, number of layers; p_g, p_{g0}, pressure in gas; p_{liq}, p_{liq0}, pressure in condensate; p_w, well-bottom pressure; p_0, p_0', native pressure; p_c, capillary pressure jump; p, pressure in the absence of capillary forces; Δp, depression; p_d, pressure of the onset of condensation; μ_g, μ_{liq}, shear viscosity in the gas and condensate; n_g, n_{liq}, mole density of the gas and condensate; c_{ig}, c_{iliq}, compositions of the gas and condensate; c_{i0}, composition of the bed mixture; N, number of components; f_g, f_{liq}, relative phase permeabilities for the gas and condensate; s, s_0, saturation by liquid phase; s_*, mobility threshold of the condensate; W, dimensionless function p_g and p_{liq}; φ_g, φ_{liq}, φ_{gmax}, quantities with the dimensions of permeability; Q, Q_0, Q_0', q, D, outputs; ξ, $\Delta\xi$, ξ_w, ξ_0, κ, a, auxiliary parameters; F, F', Φ, Φ_*, F_*, G, auxiliary functions.

REFERENCES

1. O. Yu. Dinariev, Inzh.-Fiz. Zh., 67, Nos. 1-2, 98-102 (1994).
2. A. Yu. Babeiko and O. Yu. Dinariev, Izv. Akad. Nauk SSSR, Mekh. Zhidk. Gaza, No. 6, 92-97 (1994).
3. O. Yu. Dinariev, Prikl. Math. Mekh., 58, Vyp. 6, 78-85 (1994).
4. É. Wales, Phase Equilibria in Chemical Technology, in 2 Pts. [Russian translation], Moscow (1989).
5. O. Yu. Batalin, A. I. Brusilovskii, and M. Yu. Zakharov, Phase Equilibria in Systems of Natural Hydrocarbons [in Russian], Moscow (1992).
6. Instructions for Combined Investigation of Gas and Gas-Condensate Seams and Wells [in Russian], Moscow (1980).