ON THE MOTION OF TWO-PHASE SYSTEMS IN A POROUS MEDIUM TAKING ACCOUNT OF HEAT- AND MASS-TRANSPORT PROCESSES

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The essential influence of the process of mass transport of the condensate on the filtration resistance is shown. It is explained that mass transport of residual water occurs in the isothermal filtration of gas–liquid systems.

Gas–liquid and gas—condensate systems characterized by the process of retrograde condensation are understood to be two-phase systems. The filtration of gas–liquid and gas—condensate systems has been examined in a whole series of papers (see [1-5], say). A thermodynamic model, which may serve as the basis for gas-hydrodynamic computations of the filtration of two-phase systems, based on researches in the Azerbaidzhan Institute of Petroleum and Chemistry, is discussed below. On the basis of experimental results and specific gas-hydrodynamic computations, the necessity is shown for including a number of mass-transport processes not taken into account before, into the analysis: 1) condensation; 2) mass transport of the residual water; 3) sorption processes. The ultimate goal is mainly to show the need to take account of the processes noted by the computations carried out. Let us try to formulate the general thermogas-hydrodynamic principles underlying the filtration of two-phase systems as an example of systems used in oil industry mechanics, in particular, petroleum gas systems.

As the pressure of a two-phase gas is reduced at a finite rate, the equilibrium between the liquid–gas phases is spoiled. Experimental (cylinder) and theoretical investigations in this area have shown that an essential nonuniformity should be expected in the zone near the face, and in the borehole shaft [6]. It is therefore necessary to delimit the zone in which the equilibrium and nonequilibrium condensation or degasification occurs.

The thermodynamic dissolution or condensation process can be approximated by two processes: differential and contact, where the process will be almost contact in the zone near the face, and almost differential in the more remote zone (see [7], for example). The boundary of existence of the processes is naturally defined with some degree of approximation. Taking into account the lack of knowledge of the degree of accuracy of the approximation, it must be assumed that its accuracy will increase as the integral indices of the contact process approach the differential. This latter is possible in the case of slight influence of the gas composition on the integral indices of the dissolution or condensation process. Thus, for example, experimental investigations show that the difference between contact and differential condensation (or dissolution) is 13-15% relative to the quantity of precipitated liquid in the first case, and to the quantity of gas evolved in the second case [8, 9].

The greatest admissible error in going from a multicomponent model to a pseudobinary system is naturally again within these limits.

Moreover, the experimental investigations conducted have shown that the results of cylinder investigations are not always applicable to real strata conditions. It has been established that a porous medium exerts essential influence on the thermodynamic characteristics of gas–liquid systems. The possibility of an experimental determination of the saturation pressure of a petroleum gas and the pressure of the beginning of condensation of a gas—condensate system in the presence of a porous medium has been examined.

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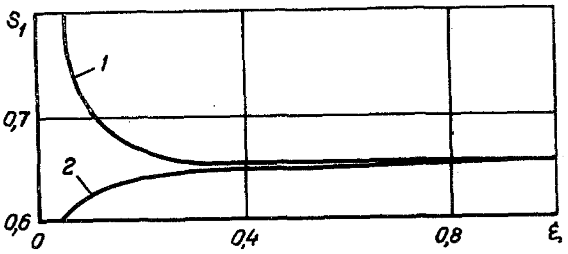

Fig. 1

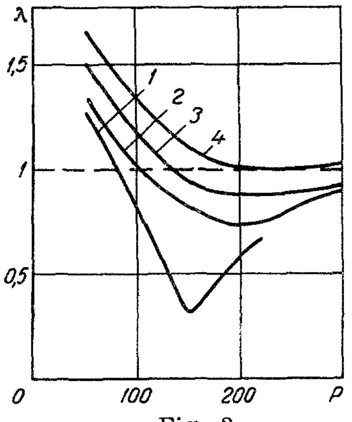

Fig. 2

Fig. 1. Dependence of petroleum saturation S_1 on the dimensionless radius ξ ($p_3 = 0.2$): 1) taking account of mass transport of residual water; 2) not taking account of mass transport of residual water.

Fig. 2. Change in relative moisture contents as a function of pressure for different t: 1) 25; 2) 50; 3) 75; 4) 100°C. P, ata.

According to the Wyckoff–Botsett curves, even a comparatively low gas content exerts an essential influence on the magnitude of the phase permeability for a liquid. Therefore, on the basis of the pressure dependence of the phase permeability, the saturation pressure of the beginning of condensation can be estimated by means of the inflection points [10, 11].

Data are presented in the literature, on the influence of inert gases on the thermodynamic characteristics of gas–liquid systems, where an increase in the quantity of inert gas results in an increase in saturation pressure [12]. Experimental investigations have shown that helium and nitrogen increase the saturation pressure of a gas–liquid system, where the presence of inert gases contributes to a faster buildup of thermodynamic equilibrium.

Qualitatively, the influence of a porous medium on the thermodynamic characteristics of gas–liquid systems can be simulated by replacing the porous medium by a gas which will not interact with the gas–liquid system, by helium, say.* It hence becomes possible to study visually the changes in the PVT properties of gas–liquid systems. Let us note that sorption effects, as well as the difference in the size of the gas inclusions and the porous medium are not taken into account here.

The above, as well as computations carried out, showed that a thermodynamic equilibrium process occurs in all practical cases of gas–liquid and gas–condensate system filtrations in a stratum, with the exception of several centimeters near the face zone. On the basis of the above, as well as taking account of the roughness in determining the reduced radius, it is proposed to consider the filtration of gas–liquid systems as a thermodynamically equilibrium process.

Keeping the above in mind, and also taking account of the lack of data on phase permeabilities for multicomponent systems, let us assume that it is rational at the present time to use a thermodynamic model of a pseudobinary system for the analysis of petroleum gas and gas–condensate systems.

Taking the pseudobinary model as basis, we obtain a system of differential equations describing the process of mass transport of the condensate, moisture, sorption processes, and degasification of the residual petroleum. Let us note that the process of mass transport of moisture can be different in nature. Thus for example, the moisture content of a gas increases as the pressure decreases for an isothermal process and the absence of a porous medium, while it decreases in gas–condensate systems on the other hand [5]. Moreover, a temperature reduction, the presence of an inert gas and porous medium, alter the mass-transport picture qualitatively [13].

Henceforth, for simplification we neglect: a) the change in gas composition; b) the change in mass of gas because of mass transport of condensate, moisture, and sorption. Let us start from the following mathematical formulation of the problem:

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*This does not refer to gas–condensate systems.

$$\operatorname{div}[\bar{v}_1\beta(P)] - \nu(P)\operatorname{div}[\bar{v}_1\alpha(P)\beta(P)] + \frac{\rho_1}{\rho_0}\left[mS_2\frac{\partial\nu(P)}{\partial\tau}\right.$$

$$\left. + \bar{v}_2\cdot\operatorname{grad}\nu(P)\right] = m\nu(P)\frac{\partial}{\partial\tau}[S_1\beta(P)\alpha(P)] - m\frac{\partial}{\partial\tau}S_1\beta(P)], \tag{1}$$

$$\operatorname{div}\left[\bar{v}_2\frac{\rho_1}{\rho_0} + \bar{v}_1\beta(P)\alpha(P)\right] = -m\frac{\partial}{\partial\tau}\left[S_2\frac{\rho_1}{\rho_0} + S_1\beta(P)\alpha(P)\right], \tag{2}$$

$$-\frac{\partial S_3}{\partial\tau} = \frac{\rho_1}{\rho_0}\left[\frac{\bar{v}_2}{m}\cdot\operatorname{grad}W(P) + S_2\frac{\partial W(P)}{\partial\tau}\right], \tag{3}$$

$$-\bar{v}_1\operatorname{grad}C = \frac{\partial C_1}{\partial\tau} + \gamma_1\frac{\partial S_1}{\partial\tau} + \frac{\partial C}{\partial\tau}, \tag{4}$$

$$\bar{v}_1 = -\frac{kf_1}{\mu_1(P)}\cdot\operatorname{grad}P;\ \bar{v}_2 = -\frac{kf_2}{\mu_2(P)}\cdot\operatorname{grad}P, \tag{5}$$

$$\nu(P) = b_1P^2 + b_2P + b_3, \tag{6}$$

$$S_1 + S_2 + S_3 = 1, \tag{7}$$

$$W(P) = \frac{A}{P} + C_0;\ \frac{\partial C_1}{\partial\tau} = \beta_1(C - \Gamma C_1). \tag{8}$$

Let us analyze the influence of each of the noted factors separately. The following have been shown on the basis of numerous gas-dynamic investigations of the filtration of gas–liquid systems taking account of the above-mentioned mass-transport processes according to (1)-(8).

1. The process of mass transport of condensate influences the filtration resistance substantially (see, for example, [5]).

2. Mass transport of the residual water occurs in the isothermal filtration of gas–liquid systems. The change in saturation by the liquid as a function of the dimensionless radius is presented in Fig. 1 taking account of the mass transport of residual liquid (1) and without it (2). The curves mentioned have been constructed for the case when the liquid and gas occupy the volume of pore space being freed after removal of the water, in conformity with the change in phase permeability. The above permits the assumption, for example, that the inconsistency between the results of a number of theoretical and experimental deductions and practical data characterizing the development of petroleum gas strata, can be explained namely by not taking account of the mass transport of residual water in the filtration of gassed petroleum.

In order to determine the possibility of water passing through the petroleum into the gas phases, tests were conducted to verify the presence of mass transport of water into the phase through a petroleum column for an isothermal process.

Evaporation of the residual water was also investigated in the isothermal filtration of a gas in a plane-radial stratum. According to the results of gas-hydrodynamic investigations, the filtration resistance for the gas diminished threefold because of evaporation of the residual water. To verify the confidence of the results obtained for the analysis, special experiments were formulated. It has consequently been established that water saturation diminishes in an isothermal process in the direction of the output end of the sample, which is in complete agreement with theoretical computations. Let us note that the process of mass transport of residual water should be carried out taking account of the presence of a porous medium and temperature changes.

By an example, let us show the influence of a temperature change on the process of mass transport of moisture. Thus, for example, for a definite gas composition W depends on the pressure and temperature [13]:

$$\frac{dW}{dP} = \frac{\partial W}{\partial P} + \frac{\partial W}{\partial t}\mu, \quad \mu = \frac{dt}{dP}. \tag{9}$$

If the pressure diminishes in the zone near the face during utilization of the borehole, then evaporation of the bound water will occur for $dW/dp < 0$ and condensation of the water vapor for $dW/dp > 0$. From the viewpoint of phase transitions, a natural gas–water system is in the normal evaporation range for the

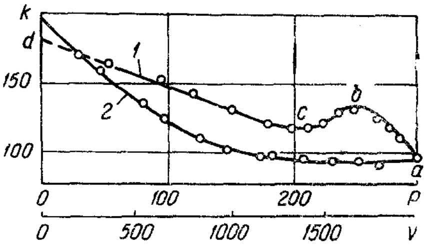

Fig. 3

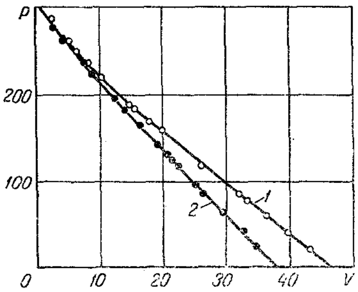

Fig. 4

Fig. 3. Change in sample permeability as a function of pressure (ata) and volume (cm^3) of the gas passed through it: 1) K = K(P); 2) K = K(V). K, md.

Fig. 4. Pressure (ata) change in the gas volume (m^3): 1) taking account of sorption processes; 2) without taking account of sorption processes.

majority of gas strata. Hence, the first member in the right side of (9) characterizes the increase in moisture content because of the diminution in pressure, and the second characterizes the change in moisture content because of temperature reduction due to the Joule–Thompson effect. Taking account of the above, it can be noted that drainage of the zone near the face occurs for*

$$\left|\frac{A_1}{P_2}\right| > \left|\left(\frac{1}{P}\,\frac{\partial A_1}{\partial \tau} + \frac{\partial C}{\partial t}\right)\mu\right|. \tag{10}$$

The results of computations for methane are presented in Fig. 2.

It is seen from the figure that for definite relationships between the initial strata temperatures, the strata and face pressures, and the quantities μ in the development of gas deposits by depletion in the zone near the face, the following can occur: a) evaporation of the bound water; b) evaporation of the bound water in the first development period and condensation of the water vapor in the second period with subsequent evaporation of the water; c) condensation of the water vapor from the gas in the first stages with subsequent evaporation of the water; 4) condensation of the water vapor.

3. Experimental investigations conducted in recent years have shown that at comparatively high pressures, particularly for a gas of complex composition (a gas—condensate system), sorption processes (curve 2, Fig. 3) can exert a perceptible influence on the filtration process. Presented in this figure is the isotherm K = K(P) (curve 1) which indirectly characterizes the sorption processes. The section ab on the K = K(P) curve shows the increase in sample permeability because of gas desorption upon reduction of the pressure from P_0 to P_1. The section bc corresponds to a diminution in permeability because of precipitation of the condensate in the stratum as the pressure is reduced from P_1 to P_2. The section cd shows the increase in permeability because of desorption and normal evaporation.

Let us note that a quantitative estimate of such a phenomenon is quite important. Tests conducted on the indirect determination of the quantity of sorbed material at high pressures and temperatures showed this by the change in specific gravity of the gas emerging from a vessel with a porous medium.

Curves of the pressure drop for gas—condensate systems (1) and for a dry gas (2) are presented in Fig. 4. As is seen from Fig. 4, taking account of just sorption processes results in a 15-20% increase in the initial gas reserves in the stratum. Let us note that the presence of clay or clayey materials, which possess a high sorptivity as compared with sand, increases the quantity of sorbed material. A direct determination of the quantity of sorbed gas by means of the change in weight and the material balance equation lowers the percentage presented somewhat, leaving it perceptible in practice.

Let us note that a number of exact self-similar and approximate solutions has been obtained by means of (1)-(9).

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*The phase transitions were not taken into account in the determination, i.e., the latent heat of vapor formation of the water probably has very little influence on the shaping of the temperature mode.

A whole series of effects taking place during development of petroleum and gas –condensate deposits, as well as in sinking boreholes, can be explained by heat- and mass-transport processes.

In particular, drainage of the residual water, sorption processes are one of the causes for an increase in the coefficient of productivity of gas – condensate deposits during development by depletion.

Certain complications in cementing boreholes can be explained by the moisture productivity in cement rock.

NOTATION

β_1, A, A_1, Γ, b_1, b_2, b_3, C_0	are the constant coefficients;
P_0, P_1, P_2, P_3	are the pressures of the experiment, of the beginning of condensation, of maximum condensation, and on the borehole outline, respectively;
$\bar{v}_1$, $\bar{v}_2$	are the filtration velocity of the condensate and the gas, respectively;
$\beta(P)$, $\alpha(P)$	are the coefficient of volume shrinkage and solubility of the gas in the liquid;
$\nu(P)$	is the quantity of stable condensate in the gas phase;
S_1, S_2, S_3	are the saturation of the stratum with condensate, gas, water, respectively;
τ	is the time;
m, K, h	are the porosity, permeability, and power of the stratum, respectively;
μ_1, μ_2	are the liquid and gas viscosity, respectively;
ρ_1, ρ_2	are the gas phase density under stratum and atmospheric conditions;
f_1, f_2	are the phase permeability of the liquid and gas, respectively;
t	is the temperature;
λ	is the ratio of moisture content on the face to the moisture content under stratum conditions;
V	is the gas volume;
W	is the moisture content of the gas phase;
γ_1	is the specific gravity of the liquid condensate;
C, C_1	are the quantity of sorbed material in the gas phase and in the sorbent.

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