THEORETICAL INVESTIGATIONS OF FILTRATION PROCESS OF HYDROCARBON MIXTURES IN POROUS MEDIA

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ABSTRACT

A mathematical model is developed which enables one to calculate the hydrodynamic and thermodynamic characteristics of the process of filtration of hydrocarbons in the stratum. A theoretical investigation is performed of the effect of formation and destruction of a condensate plug under conditions of filtration of a binary mixture of hydrocarbons (methane–n-butane) in a one-dimensional model of gas-condensate stratum. The possibility of the existence of periodic regimes of filtration processes is shown.

INTRODUCTION

Many filtration processes lead to two-phase flow problems with distributed in the space phase transitions in a porous medium, taking place not on the surface, as, for example, in the classical Stefan problem, but also in the spatial domain. Formation of two-phase flows is typical for processes of oil and gas production when the fluid consists of a number of chemically different components in different aggregate states, for example, evaporation of gas in the flow of saturated oil, condensate in the flow of gaseous mixture of hydrocarbons [1-2].

Gas condensate is a complex mixture of methane and higher derivatives of the methane series. The phase diagram of such a mixture contains the so-called "retrograde region", i.e., a region in which a pressure decrease may cause the formation of retrograde liquid evaporating with further pressure decrease [3].

The purpose of this paper is a theoretical investigation of the peculiarities filtration the mixture of hydrocarbons in a porous medium on an example of a binary mixture methane-n-butane having a characteristic retrograde region on the phase diagram.

NOMENCLATURE

C	Methane mole fraction
c	Mole fraction
f	Relative phase permeability function
k	Absolute permeability
m	Porosity
n	Molar concentration
P	Pressure
R	Universal gas constant
T	Temperature
s	Gas saturation
U	Velocity
v	Molar volume
x	Cartesian axis direction
Y	Number of moles
z	Compressibility coefficient

Special characters

μ	Viscosity

Subscripts

i	1-CH_4, 2-C_4H_{10}
j	1-gas, 2 -liquid

MATHEMATICAL MODEL

Consider the one-dimensional gas-condensate reservoir consisting of a porous skeleton and two-component mixture of hydrocarbons methane–n-butane. The phase diagram of such a mixture is shown in Figure 1.

At the initial time the strata pressure is P1, which does not change in time, and the hydrocarbon mixture is in gaseous state (point 1). We denote the pressure near the well as P2 <P1. Due to the pressure difference the flow of the hydrocarbon mixture to the well occurs. We introduce the characteristic length L, on which the pressure changes from P1 to P2 (Figure 2)

The pressure P2 corresponds to the state 2, which is a two-phase system. During filtration of hydrocarbons in the porous medium pressure of the mixture changes continuously, passing through the phase transition pressure P_{ph} (the point is singular and function of gas saturation is discontinuous in it).
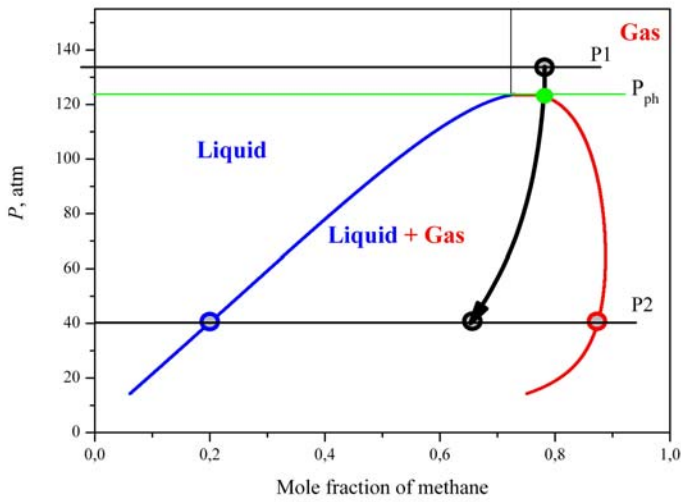
Figure 1 The pressure-composition phase diagram of methane–n-butane binary mixture
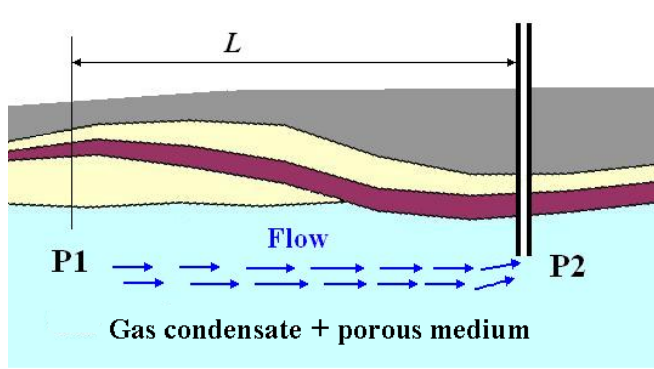

Figure 2 Statement of the problem

Thus, filtration of two-phase two-component mixtures of hydrocarbons with the phase transition occurs.

The unsteady processes occurring during filtration of a hydrocarbon mixture in a porous reservoir were simulated in a one-dimensional approximation under isothermal conditions.

Structurally, the model consists of two parts, namely, the hydrodynamic part, which describes the process of two-phase filtration in a porous medium in the Darcy law approximation, and the thermodynamic part, within which the equations of state for mixture are used to calculate the compressibility coefficients of the mixture and the parameters of phase equilibrium of the system in the vapor and liquid phases.

We write the conservation equations for each component

$$m \frac{\partial}{\partial t}\left(\sum_j c_{ij} n_j s_j\right) + \frac{\partial}{\partial x}\left(\sum_j c_{ij} n_j U_j\right) = 0 \qquad (1)$$

The equations of motion in view of generalized Darcy law [4] have the form

$$U_j = -k \frac{f_j(s_j)}{\mu_j} \frac{\partial P}{\partial x} \qquad (2)$$

The obtained hydrodynamic equations are complemented by the equations of state for the liquid and vapor phases, by the conditions of thermodynamic equilibrium, and by the boundary and initial conditions.

We write equations of state for the gas and liquid phases in terms of compressibility coefficients

$$P = n_j z_j RT \qquad (3)$$

The properties of binary mixture in the vapor and liquid phases were calculated using the generalized cubic four-coefficient equation of state of the Van der Waals type specially derived for natural oil-gas condensate mixtures in the case of pressures up to 100 MPa and temperatures up to 500 K [5]

$$P = \frac{R_\mu T}{v - b} - \frac{a}{(v + c) \cdot (v + d)} \qquad (4)$$

where $R_\mu = R/\mu$.

Cubic equation (4) may be conveniently written with respect to compressibility coefficient as

$$z^3 + (C + D - B - 1)z^2 + (A - B \cdot C + C \cdot D \\ - B \cdot D - D - C)z - (B \cdot C \cdot D + C \cdot D + A \cdot B) = 0 \qquad (5)$$

where

$$A = \frac{ap}{R_\mu^2 T^2}, \quad B = \frac{bp}{R_\mu T}, \quad C = \frac{cp}{R_\mu T}, \\ D = \frac{dp}{R_\mu T}, \quad z = \frac{pv}{R_\mu T} \qquad (6)$$

b, c, and d are the coefficients which are constant for the given substance, $a = a_c \varphi(T)$, a_c – is a constant, and φ is the temperature function. The values of parameters of the equation of state for components of oil-gas condensate systems are borrowed from [5, 6].

The equilibrium concentrations of the components in both phases depend on the pressure and satisfy to a condition

$$\sum_i c_{ij}(P) = 1 \qquad (7)$$

Volume fractions of the phases are related by

$$\sum_j s_j = 1 \qquad (8)$$

NUMERICAL METHOD

We introduce a function of gas saturation s. Then saturation is written as 1-s. We introduce the following notation: $c_1(P) = c_{CH4,1}$ – mole fraction of methane in the gas, $c_2(P) = c_{CH4,2}$ – mole fraction of methane in the liquid. Then the mole fraction of butane in the gas is expressed as 1 - c_1, in a liquid - 1 - c_2.

Given the accepted notation system (1 - 2) can be written as

$$m \frac{\partial}{\partial t}\left(c_1 n_1 s + c_2 n_2 (1-s)\right)$$

$$-\frac{\partial}{\partial x}\left(k\left(c_1 n_1 \frac{f_1(s)}{\mu_1} + c_2 n_2 \frac{f_2(s)}{\mu_2}\right)\frac{\partial P}{\partial x}\right) = 0,$$

$$m \frac{\partial}{\partial t}\left((1-c_1)n_1 s + (1-c_2)n_2(1-s)\right) \tag{9}$$

$$-\frac{\partial}{\partial x}\left(k\left((1-c_1)n_1 \frac{f_1(s)}{\mu_1} + (1-c_2)n_2 \frac{f_2(s)}{\mu_2}\right)\frac{\partial P}{\partial x}\right) = 0.$$

We introduce the notation

$$Y_1 = m(c_1 n_1 s + c_2 n_2 (1-s)),$$
$$Y_2 = m((1-c_1)n_1 s + (1-c_2)n_2(1-s)). \tag{10}$$

Here, new variables are the number of moles of methane and butane in the gas and liquid phases, and thus introduced the functions are continuous.

In view of equations (10) and (3) a system of equations (9) can be written as

$$\frac{\partial Y_1}{\partial t} = \frac{k}{RT}\frac{\partial}{\partial x}\left(\left(c_1 \frac{f_1(s)_1}{\mu_1 z_1} + c_2 \frac{f_2(s)}{\mu_2 z_2}\right)P\frac{\partial P}{\partial x}\right),$$

$$\frac{\partial Y_2}{\partial t} = \frac{k}{RT}\frac{\partial}{\partial x}\left(\left((1-c_1) \frac{f_1(s)}{\mu_1 z_1} + (1-c_2)\frac{f_2(s)}{\mu_2 z_2}\right)P\frac{\partial P}{\partial x}\right). \tag{11}$$

Function of gas saturation is determined by

$$s = \frac{C - c_2(P)}{c_1(P) - c_2(P)} \tag{12}$$

where the mole fraction of methane in the mixture

$$C = \frac{Y_1}{Y_1 + Y_2} \tag{13}$$

Adding the equations in (9) and substituting the expression for the density from equation (3) an equation for the pressure

$$\frac{\partial P D_{22}}{\partial t} = \frac{\partial}{\partial x}\left(\left(\frac{f_1(s)}{\mu_1 z_1} + \frac{f_2(s)}{\mu_2 z_2}\right)kP\frac{\partial P}{\partial x}\right) \tag{14}$$

where $D_{22} = m\left(\frac{s}{z_1} + \frac{1-s}{z_2}\right)$.

The new system of equations consists of two equations for the number of moles of methane and butane (11) and the equation for the pressure (14). In contrast to the original system (1) - (2) a new system of equations is written for the variables that change continuously. The system of equations (11) - (14) closes the initial and boundary conditions for the variables Y_1, Y_2 and P: $P(x, t = 0) =$ P1, $P(x = 0, t) =$ P1, $P(x = L, t) =$ P2, $Y_1(x, t=0) = Y_{10}$, $Y_1(x=0, t) = Y_{10}$, $Y_2(x, t = 0) = Y_{20}$, $Y_2(x=0, t) =Y_{20}$.

Discrete analogs of Eqs. (11) and (14) are obtained by integration with respect to control volume [7]. A fully implicit scheme is used in the case of approximation in time. The double-sweep method is used for solving discrete pressure equation.

RESULTS

The filtration process is a binary mixture of hydrocarbons (methane–n-butane) in a porous medium was simulated. The following values of input parameters were specified: the initial mole fraction of methane – 0,75, $T = 310$ K, $k = 1.3 * 10^{-11}$ m^2, $m = 0,35$, $L = 3$ m, P1 = 125 atm.

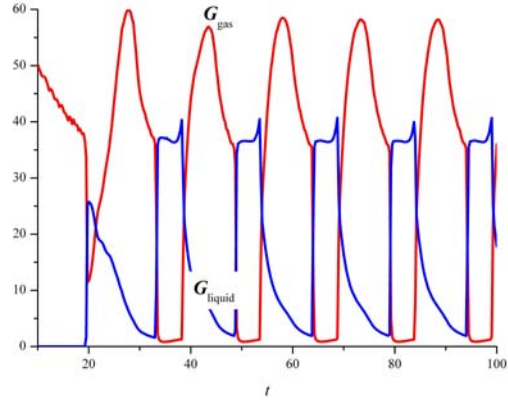The calculated dependences of flows of gas and liquid phases at the output (at $x = L$) are shown in Figure 3.

Figure 3 The time dependences of relative phase flows at $x=L$

The periodic form of the curves is primarily associated with the behavior of relative phase permeability functions (Figure 4).
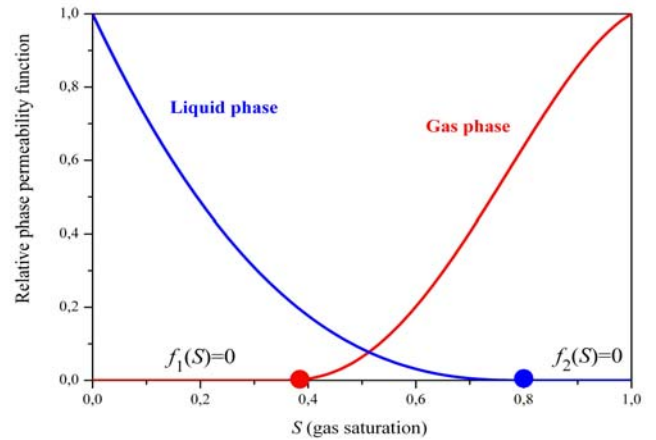

Figure 4 Relative phase permeability functions

In the typical dependence of permeability via gas saturation for hydrocarbon mixtures, there are areas in which the relative phase permeability functions are equal to 0. Accordingly, the phase velocities in these areas are equal to 0. Gas saturation under the given conditions varies from 0.35 to 0.55. At the same time the liquid phase, in contrast to gas, does not stop (see Figure 4). Due to lower viscosity flow rate and velocity of the gas phase are greater than the flow rate and velocity of the liquid phase (Figure 3).

Thus, we propose the following mechanism to explain the oscillation of the filtration process of hydrocarbons in a porous medium. At sufficiently high gas saturation (s = 0,6 - 0,8) both gas and liquid are freely filtered, and due to the greater viscosity of the fluid filtration rate is significantly lower than the rate of filtration of the gas phase. Over time, fluid is accumulated, and the gas saturation decreases and, consequently, gas permeability is reduced, that leads to a decrease in gas velocity. Due to the pressure drop there is an additional condensation of the fluid, that leads to further reduction of gas saturation.

Upon reaching the gas saturation values of 0.38 (Figure 4) relative permeability and the speed of the gas phase are equal to 0. In this case the fluid velocity reaches its maximum value.

Then the front, characterized by zero velocity of the gas phase, is moving toward the exit with the velocity of the liquid phase. A typical distribution of the parameters is shown in Figure 5 (a). When the front reaches the exit gas flow rate drops to zero, and the flow of the liquid phase increases to a maximum value (Figure 5 (b)). Liquid phase permeability reduction leads to decrease in the liquid phase flow up to 0 (Figure 5 (c)). Then there is condensation front, which moves against the flow (Figure 5 (d)). Behind the front of the condensation the liquid phase is formed and gas saturation is set to at which the rate of filtration of gas and liquid non-zero. The gas saturation value corresponds to nonzero velocities of gas and liquid filtration. Then the entire filtration cycle is repeated.
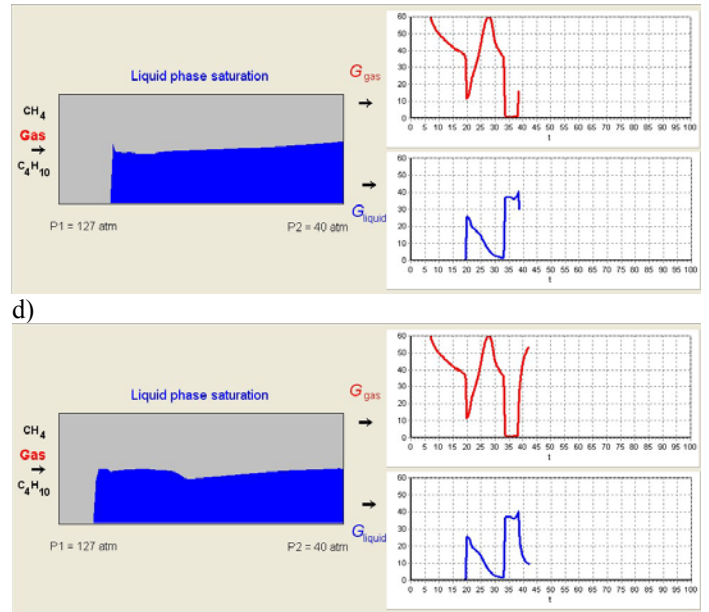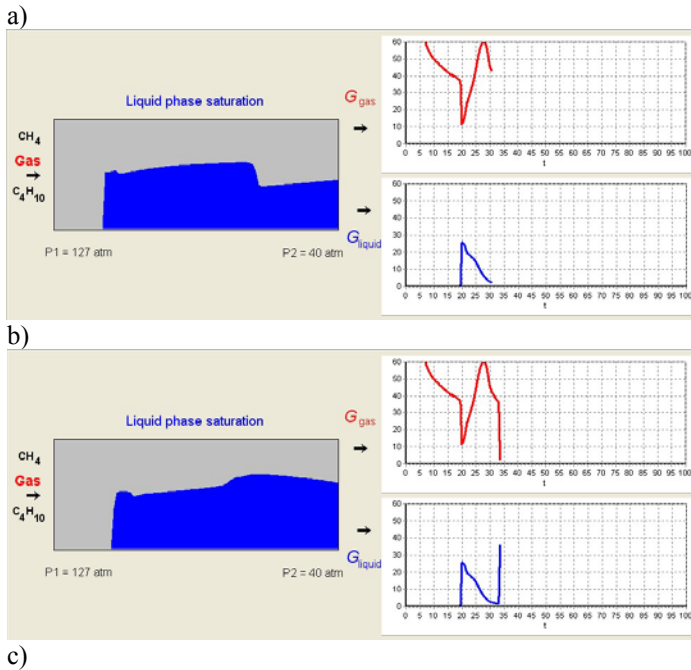
a)

b)

c)

d)

Figure 5 Ddistribution of the parameters at different times

CONCLUSION

The investigations show the possibility of periodic solutions of the two-phase filtration of hydrocarbon mixtures in a porous medium. It is shown that the periodic solution arises as a result of the combined effect of permeability and retrograde features of the phase diagram of the hydrocarbon system. The mechanism of wave effects arising from the development of gas condensate fields is proposed. The obtained results may be useful in developing methods of wave impact on the gas-condensate reservoir in order to increase its productivity.

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