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Some features of identification modeling of oil and gas displacement

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Abstract. *The gas flooding technology is considered promising and is currently widely used in the main oil recovering regions, however, when only gas is injected into the formation, its breakthrough into producing wells is possible due to the fact that the gas mobility is significantly higher than the oil mobility of. The paper proposes an identification model of the hydrocarbon displacement from the reservoir, where the pressure gradient is assumed for the input effect, the displacement factor is assumed for the output reaction, and the proportion of the pore volume of the injected gas and water is taken as the argument of the model*

Keywords. water flooding · gas injection · water alternating gas · oil recovery · reservoir · pressure gradient

Mathematics Subject Classification (2010): 76A05, 35J05

1 Introduction

The gas flooding methods and water alternating gas (WAG) injection can be considered as the most promising techniques along many of oil recovery increasing technologies used in low-permeable terrigenous reservoirs (oil recovery coefficient does not exceed 0.30) [3, 5, 7, 10, 12, 15].

The gas flooding technology is considered effective and is widely used currently. However, when the gas is injected into the formation, its breakthrough into producing wells is possible given that the mobility of gas is significantly higher than the oil mobility.

Since gas breakthroughs greatly reduce the effectiveness of the method, it becomes expedient to inject water-gas mixture into the reservoir, the technology of which, by combining methods of gas injection is called water-gas flooding.

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The features of development of the productive reservoirs with low filtration characteristics and low oil recovery factor were investigated on the basis of physical modeling of the method of WAG injection in low-permeable reservoirs [5, 14]. Various technologies of WAG (sequentially, by variable, as well as gas-pressure mode) were considered under conditions of residual and initial oil saturation of the reservoir model, the type of injected gas (simultaneously extracted, dry hydrocarbon gases and nitrogen) and reservoir permeability.

2 Statement and method of solution

The characteristic features of the major indicators change under oil displacement at sequential and alternate injection of associated gas and water into the reservoir model, presented in Fig. 2.1, allows us to identify, along with a quantitative assessment, some qualitative features of the behavior of the oil displacement factor and the pressure gradient.

As can be seen from Fig. 2.1, the dynamics of the qualitative change in the displacement factor vs. injected gas volume and water occurs monotonously, and in the case when displacement occurs by a gas-liquid system, it is also monotonous, but with some delay. While the dynamics of qualitative changes in the pressure gradient changes, as a rule, not monotonously, and in the case of displacement by a gas-liquid system, the pressure drop is pulsatory.

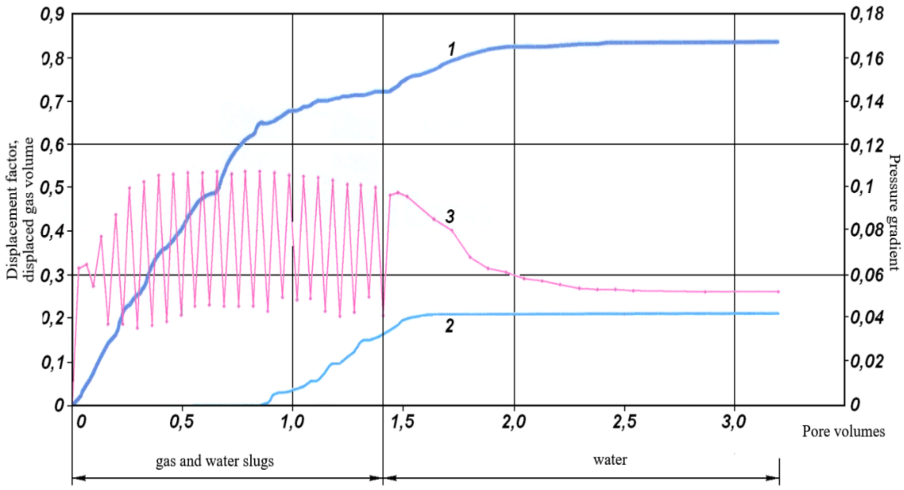

Fig. 2.1. Characteristic features of the main indicators of oil displacement under alternate injection of associated gas and water into the reservoir model: 1 – oil displacement coefficient, 2 - accumulated volume of displaced gas, 3 - pressure gradient

To mathematically describe the results of experimental studies of the bed stimulation in low-permeable terrigenous reservoirs, as a rule, conventional methods of oil and gas production simulation are used [3, 6, 9, 10, 11, 12]. Along with this, the use of identification modeling methods, which are understood as constructing models that establish connections between input and output characteristics that take into account only the nature of the functioning of the object, can be very effective and expedient [1, 2, 7, 8, 13].

Taking into account the above mentioned, an identification model of the oil and gas displacement is proposed below, where a pressure gradient is assumed for the input effect, a displacement factor is assumed for the output reaction, and the proportion of the pore volume of injected gas and water is taken as the argument of the model:

$$\alpha_2 \frac{d^2 K_2}{dV^2} + \alpha_1 \frac{dK_2}{dV} + K_2 = \beta_0 \nabla P + \beta_1 \frac{d\nabla P}{dV} + \beta_2 \frac{d^2 \nabla P}{dV^2} \tag{2.1}$$

where K is the oil displacement coefficient; ∇P - pressure gradient; V is the fraction of the pore volume of the injected gas and water; $\alpha_1,\ \alpha_2,\ \beta_0,\ \beta_1,\ \beta_2$ are constant coefficients.

The identification differential equation (2.1), under certain reservoir conditions and ratios of constant coefficients $\alpha_1,\ \alpha_2,\ \beta_0,\ \beta_1,\ \beta_2$ can describe qualitatively all the features of the oil and gas displacement.

For a quantitative description of the oil and gas displacement, it is necessary to formulate and solve inverse problems to determine constant coefficients based on experimental or field information.

The process of oil and gas displacement is considered, while it is assumed that the pressure gradient is a constant value equal to ∇P_0. Then, under the accepted assumptions, the differential equation (2.1) can be written as

$$\alpha_2 \frac{d^2 K_2}{dV^2} + \alpha_1 \frac{dK_2}{dV} + K_2 = \beta_0 \nabla P_0. \tag{2.2}$$

The solution of the differential equation (2.2), under zero initial conditions, has the form

$$K_2 = \beta_0 \nabla P_0 \left[1 + \frac{k_2}{k_1 - k_2} \exp(k_1 V) - \frac{k_1}{k_1 - k_2} \exp(k_2 V) \right], \tag{2.3}$$

$$k_{1,2} = \frac{-\alpha_1 \pm \sqrt{\alpha_1^2 - 4\alpha_2}}{2\alpha_2}.$$

Since, as noted above, the change in the displacement coefficient from the fraction of the pore volume of the injected gas and water occurs monotonously, in order to fulfill this condition, it is necessary that

$\alpha_1^2 \geq 4\alpha_2$ at $\alpha_1 \rangle 0, \alpha_2 \rangle 0$.

Naturally, at certain values of $\alpha_1,\ \alpha_2$ there can be both a simple monotonic change and a monotonic change with a delay (S-shaped change) of the displacement coefficient parameter.

The characteristic qualitative curves for the case under consideration are shown in Fig. 2.2. Now we consider the process of displacement of oil and gas systems from the reservoir, when the displacement coefficient at a certain stage is a constant value equal to K_{20}. Then, under the accepted assumptions, the differential equation (2.1) can be written as

$$\beta_2 \frac{d^2 \nabla P}{dV^2} + \beta_1 \frac{d\nabla P}{dV} + \beta_0 \nabla P = K_{20}. \tag{2.4}$$

The solution of the differential equation (2.4), under zero initial conditions, has the form

$$\nabla P = \frac{K_{20}}{\beta_0} \left[1 + \frac{k_4}{k_3 - k_4} \exp(k_3 V) - \frac{k_3}{k_3 - k_4} \exp(k_4 V) \right], \tag{2.5}$$

$$k_{3,4} = \frac{-\beta_1 \pm \sqrt{\beta_1^2 - 4\beta_0\beta_2}}{2\beta_2}.$$

In order for the change in the pressure gradient to occur not monotonously, and also, under certain conditions, to have a pulsating character, it is necessary that the conditions are met, it is necessary that $\beta_1^2 \langle 4\beta_0\beta_2$ at $\beta_0 \rangle 0, \beta_1 \rangle 0, \beta_2 \rangle 0$.

It is obvious that at certain values $\beta_0,\ \beta_1,\ \beta_2$ can have both a simple non-monotonic change and a pulsational change in the pressure gradient parameter, the characteristic qualitative curves of which are shown in Fig. 2.3 and 2.4.

After identifying the qualitative features of the processes of displacement of oil and gas systems from reservoirs, the inverse problem of determining the constant coefficients of the identification model is considered below, for a situation where the process occurs at a constant pressure gradient.

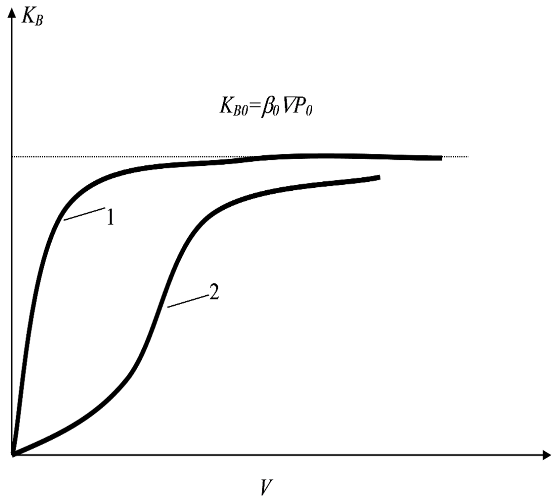

Fig. 2.2 - Characteristic qualitative curves of the oil displacement coefficient at a constant pressure gradient: 1 - inertia-free change in the oil displacement coefficient, 2 - S-shaped change oil displacement coefficient

Then the determination of the coefficients of the model $\alpha_1, \alpha_2, \beta_0$ is reduced to solving the inverse problem of the differential equation (2.2), and the coefficient β_0 can be determined from the stationary state of the process when the relation from which the coefficient is obtained is fulfilled

$$\beta_0 = \frac{K_{20}}{\nabla P_0}. \tag{2.6}$$

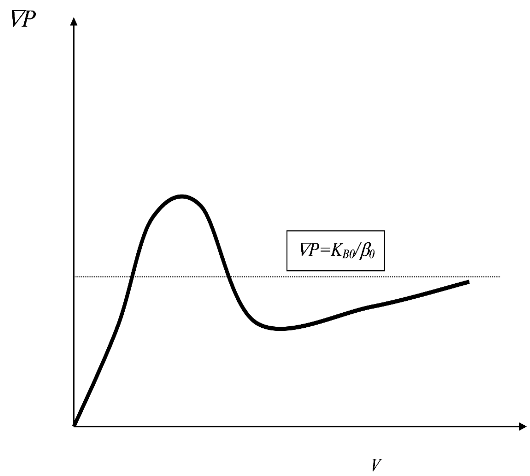

Fig. 2.3. Characteristic curve of non-monotonic change in the oil pressure gradient at a constant value of the displacement coefficient

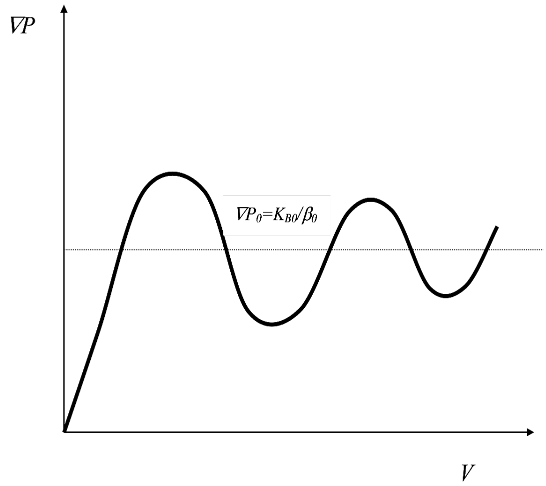

Fig. 2.4. The characteristic curve of the pulsation changes of the oil pressure gradient at a constant value of the displacement coefficient

To determine the coefficients α_1, α_2 we integrate the differential equation (2.2) with respect to the parameter V, as a result of which we can write

$$\alpha_2 \left(\frac{dK}{dV} - \left. \frac{dK}{dV} \right|_{V=0} \right) + \alpha_1 \left(K - K|_{V=0} \right) + \int_0^V K dV = \beta_0 \nabla P_0 V.$$

After some transformations, the last dependency can be represented as follows

$$\frac{\beta_0 \nabla P_0 V - \int_0^V K dV}{\frac{dK}{dV} - \left. \frac{dK}{dV} \right|_{V=0}} = \alpha_1 \frac{K - K|_{V=0}}{\frac{dK}{dV} - \left. \frac{dK}{dV} \right|_{V=0}} + \alpha_2 \qquad (2.7)$$

The resulting expression (2.7) is the main one for the proposed method for determining the coefficients α_1, α_2 of the identification model (2.2).

As can be seen, in coordinates $Y = \frac{\beta_0 \nabla P_0 V - \int_0^V K dV}{\frac{dK}{dV} - \left. \frac{dK}{dV} \right|_{V=0}}$ and $X = \frac{K - K|_{V=0}}{\frac{dK}{dV} - \left. \frac{dK}{dV} \right|_{V=0}}$ changes in the values of the oil displacement coefficient in the plane of the transformants are represented by a straight line, the angle of inclination of which is determined by α_1 and at the intersection of the straight line with the ordinate $Y = \frac{\beta_0 \nabla P_0 V - \int_0^V K dV}{\frac{dK}{dV} - \left. \frac{dK}{dV} \right|_{V=0}}$, the value of α_2.

Having data on changes in the values of the oil displacement coefficient, the values for any value $\frac{dK}{dV}$ of V are calculated, after which unknown values α_1 and α_2 are determined.

To determine the coefficients of the model $\beta_0, \beta_1, \beta_2$ situations are considered when the process occurs at a constant oil displacement coefficient, while the determination of the coefficients is reduced to solving the inverse problem of the differential equation (2.4), and the coefficient β_0 is also determined by the stationary state of the process, when the ratio from which the coefficient is obtained, in accordance with equation (2.6)

$$\beta_0 = \frac{K_{20}}{\nabla P_0}.$$

By performing some transformations similar to the above, the differential equation (2.4) reduces to the following dependence

$$\frac{K_0 V - \beta_0 \int_0^V \nabla P dV}{\frac{d\nabla P}{dV} - \left. \frac{d\nabla P}{dV} \right|_{V=0}} = \beta_1 \frac{\nabla P - \nabla P|_{V=0}}{\frac{d\nabla P}{dV} - \left. \frac{d\nabla P}{dV} \right|_{V=0}} + \beta_2 \qquad (2.8)$$

The resulting expression (2.8) is the main one for the proposed method for determining the coefficients β_1, β_2 of the identification model (2.4).

As can be seen, in coordinates $\frac{K_0 V - \beta_0 \int_0^V \nabla P dV}{\frac{d\nabla P}{dV} - \frac{d\nabla P}{dV}\big|_{V=0}}$ and $\frac{\nabla P - \nabla P|_{V=0}}{\frac{d\nabla P}{dV} - \frac{d\nabla P}{dV}\big|_{V=0}}$ changes in the values of the oil displacement coefficient in the plane of the transformants are represented by a straight line, the angle of inclination of which is determined by β_1, and at the intersection of the straight line with the ordinate $\frac{K_0 V - \beta_0 \int_0^V \nabla P dV}{\frac{d\nabla P}{dV} - \frac{d\nabla P}{dV}\big|_{V=0}}$, the value of β_2.

Having data on changes in the values of the pressure gradient, the values for any value $\frac{d\nabla P}{dV}$ of V are calculated, after which unknown values β_1 and β_2 are determined.

To test the proposed method of constructing an identification displacement model, we will use the results of experimental data (Fig. 2.1) of the dynamics of changes in the displacement coefficient of oil, with sequential injection of simultaneously extracted gas and water into the reservoir model, under conditions of initial oil saturation, a fragment of which is shown in Fig. 2.5 (row 1).

To describe the dynamics of changes in the oil displacement coefficient, one can use the differential equation (2.2), since the solution of the latter, at certain parameter values, has a characteristic behavior of the curve (Fig. 2.2) corresponding to the curve shown in Fig. 2.5.

First, the coefficient β_0 is determined by the stationary state of the process, when the ratio $K_{20} = \beta_0 \nabla P_0$ from which the coefficient is obtained is fulfilled, in accordance with equation (2.6)

$$\beta_0 = \frac{K_{20}}{\nabla P_0} = \frac{0,6}{0,07} = 8,58 \frac{\text{m}}{\text{MPa}}.$$

The results of calculations based on the ratio (2.7), based on data on the dynamics of changes in the oil displacement coefficient during sequential injection of simultaneously produced gas and water into the reservoir model under conditions of initial oil saturation (Fig. 2.1 and 2.5), are presented in Fig. 2.6.

The analysis of Fig. 2.6 shows that in Y – X coordinates, the initial data is transformed into a straight line, as a result of processing which the following values were obtained for the parameters α_1 and α_2:

$\alpha_1 = 8,29238, \ \alpha_2 = 0,70531.$

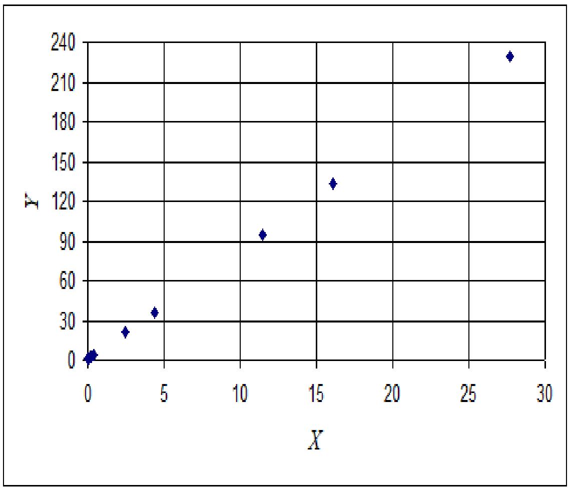

Fig. 2.5. A fragment of the dynamics of changes in the oil displacement coefficient during sequential injection of simultaneously produced gas and water into the reservoir model under conditions of initial oil saturation: 1 - experimental data, 2 - calculated data

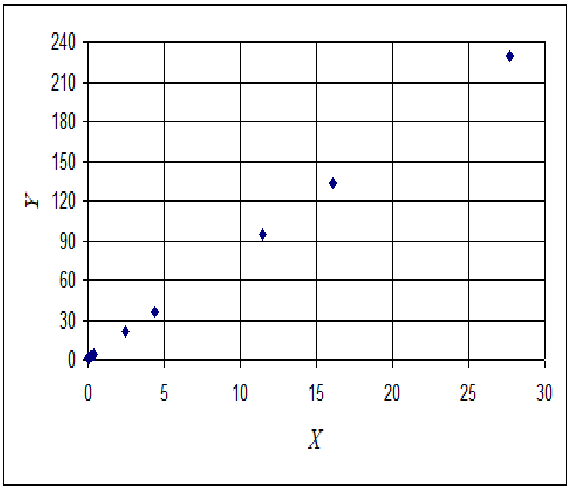

Fig. 2.6. Calculation results based on experimental data on the dynamics of changes in the oil displacement coefficient, with sequential injection of simultaneously produced gas and water into the reservoir model, under conditions of initial oil saturation

Substituting the found values β_0, α_1 , α_2 and the corresponding value of the pressure gradient $\nabla P_0 = 0.07$ MPa/m into the differential equation (2.2) and solution (2.3), the following expressions are obtained:

$$0,70531\frac{d^2K_2}{dV^2} + 8,29238\frac{dK_2}{dV} + K_2 = 0,6, \tag{2.9}$$

$$K_2 = 0,6\left[1 - 1,01068\exp\left(-0,122V\right) + 0,01068\exp\left(-11,635V\right)\right], \tag{2.10}$$

$k_1 = -0,122, k_2 = -11,635.$

The results of calculations according to formula (2.10) are shown in Fig. 5 (row 2).

Comparison of the calculated data with experimental data shows a fairly good convergence, which allows us to consider the proposed identification model as corresponding to the process under study, and the calculation method for determining the parameters of the model is correct.

3 Conclusions

1. An identification model of the process of displacement of oil and gas systems from reservoirs is proposed, where the pressure gradient is assumed for the input effect, the displacement coefficient is assumed for the output reaction, and the proportion of the pore volume of the injected gas and water is taken as the argument of the model.

2. It is shown that the proposed identification model, under certain reservoir conditions and under certain ratios of constant coefficients, can describe qualitatively all the features of the processes of displacement of oil and gas systems from the deposit.

3. Inverse problems have been set and solved to determine the constant coefficients of the identification model for various situations of technological processes affecting the formation.

4. To test the proposed method of constructing an identification displacement model, the results of experimental data on the dynamics of changes in the displacement coefficient of oil, with sequential injection of simultaneously extracted gas and water into the reservoir model, under conditions of initial oil saturation, were used.

5. The results of comparing the calculated data with the experimental data showed their sufficiently good convergence, which makes it possible to consider the proposed identification model appropriate to the process under study, and the calculation method for determining the parameters of the model correct.

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