Numerical simulation of oil formation with regulated disturbances. Oil recovery quality simulation

S A Batalov1, V E Andreev2, V M Lobankov4 and V Sh Mukhametshin3

1 Ufa State Petroleum Technological University, 1, Kosmonavtov st., Ufa, Republic of Bashkortostan, 450062, Russian Federation
2 State autonomous scientific institution “Institute of strategic research of the Republic of Bashkortostan”, 129/3, October avenue, Ufa, Republic of Bashkortostan, 450075, Russian Federation
3 Ufa State Petroleum Technological University, Branch of the University in the City of Oktyabrsky, 54a, Devonskaya St., Oktyabrsky, Republic of Bashkortostan, 452607, Russian Federation

E-mail: vsh@of.ugntu.ru

Abstract The article discusses the method of numerical modeling of a functioning reservoir based on the oil recovery hydromechanics model in the hyperbolic Cauchy problem. Optimization results for reservoir formation channels (RFC) modeling reveal integer values of new models with linear parameters of hydro-resistance, piezo capacitances and piezo inductances in the dimensionless values. The solution result is an effective tool for current prediction of filtration capacity properties (FCP) of the reservoir in the elastic water-pressure mode. The deduced numerical simulation methods based on long-term reactive RFC resistances make it possible to specify the limits of quality of oil displacement with controlled excitations at its coordinate-discontinuous controls.

1. Introduction

To monitor oil and gas deposits development (OGDD), models of filtration of reservoir fluids based on parabolic wave equations are used [1, 2]. They are introduced in software systems (Roxar, Schlumberger, Landmark) and used in numerical modeling of the reservoir due to convenient user interfaces. This is justified in the early stages of the OGDD with linear filtration of formation fluids. Since the intermediate OGDD stages, conditions for nonlinear filtration of fluids arise with the need to introduce metatechnology for extraction of hard-to-recover hydrocarbon reserves (HRHR) by using new analysis [3–10] and synthesis [11–13] methods of technical implementation tools.

Based on these conditions, the work aims to clarify the limits of quality of oil displacement of the RFC with its maximum possible longitudinal FCP based on numerical simulation of the chained current tube.

The goal can be achieved using numerical modeling methods by solving two types of problems. First, when justifying the fundamental hydromechanics hyperbolic model of oil displacement [4] based on linear parameters of hydraulic resistance ($R_h$), piezo-inductance ($L_h \equiv \eta$) and piezocapacity ($C_h$), one can use the average results of petrophysics for the early and intermediate OGDD stages. Therefore, the Dupuis-Forchheimer ratio is used at the pilot operation stage:

$$\frac{\Delta P}{\Delta L} = \frac{\mu}{k} v_f + \beta \frac{\rho}{\sqrt{k}} v_f^2,$$

(1)
where \(\Delta P/\Delta L\) is pressure difference in the controlled area of the COI; \(k, \mu, m, v_y\) are the coefficient of permeability of the section of the RFC trajectory, viscosity and filtration rates of the fluid; \(\rho\) is the fluid density; \(\beta\) is compressibility of rock (\(\beta_r\)) and formation fluid (\(\beta_f\)) in total.

The second set of tasks can be solved by introducing a linear fictitious radius of the current tube (\(R\)) in the characteristic of the chain structure of the RFC [4]. Additional introduction of reduced radius \(r\) allows for studying their values as a function of permeability coefficient \(k\). Therefore, when describing fluid movement in the current tube, it is possible to use the velocity value \(v = v_y/m\), where \(m\) is the coefficient of porosity in unit fractions. When denoting the average flow rate \(v_o\) in the RFC current tube with reduced radius \(r\), the Bernoulli equation can be used:

\[
v = v_o \left( \frac{R^2 - r^2}{R^4} \right).
\]

These tasks can be solved by using controlled interwell disturbances in the water-pressure mode [4]. For this purpose, the main conclusions of the numerical values for the long-term RFC parameters are considered.

2. Methods

**Calculation of the numerical values of RFC resistances** using the expression for the filtration rate of the RFC fluid \(v_i\), commensurate with unit fractions of a centimeter per day. Therefore, fictitious radius \(R\) of the current tube for an interwell RFC and plane-parallel flow \(v\) can be represented by alternately radial and but rectangular sections. Then, for the first linear term of equation (1), flow velocity in the transformed values is

\[
v = \frac{(\Delta P km)}{(\Delta L \mu)}.
\]

On the other hand, for the additional characteristic of reduced radius \(r\) of the RFC, you can use the Bernoulli equation (2) for its current tube. Taking into account this modification, it is possible to equate right-hand sides of equations (2) and (3) to obtain measurable values of hydro-resistance. Then, in the converted coordinates of the quantities, the following relationship is obtained for the hydraulic resistance of the RFC section:

\[
R_y = \frac{\mu}{kR} = \frac{\Delta P}{\Delta L} \frac{R}{v_m(R^2 - r^2)}.
\]

Expression (4) for linear hydraulic resistance \((R_y)\) is one of the main specifying indicators of the dimensionless parameters of chain sections \(dx\) of extended trajectory \(l\) in the RFC, determined by ratio \(y = x/l\).

**Calculation of the values of piezoelectric inductance of the RFC.** To synthesize the numerical values of the linear piezoelectric inductance of the RFC, the second component of the nonlinear part of the terms of the Dupuy-Forchheimer equation (1) is used. The square of the filtration rate is calculated by formula

\[
v_y^2 = \frac{\Delta P}{\Delta L} \frac{\sqrt{f}}{\rho \beta^*}.
\]

For the Bernoulli equation (2), the plane velocity mode is converted through coefficient of porosity \(m\) to the filtration velocity whose square is calculated by formula

\[
v_y^2 = v_y^2 m^2 (R^2 - r^2)^2 / R^4.
\]

To obtain the expression for linear piezo inductance \(L_o\), you need to multiply the numerator and denominator of equation (5) by permeability coefficients \(k\) and dynamic viscosity \(\mu\) when deriving the ratio taking into account the right side of expression (6):

\[
\frac{\Delta P}{\Delta L} \frac{\sqrt{k} \mu k}{\rho \beta^* \mu k} = \frac{v_y^2 m^2 (R^2 - r^2)^2}{R^4}.
\]

Therefore, in the final form, hydraulic piezo inductance is calculated by formula

\[
L_o = \frac{k}{\mu \beta^*} \frac{\Delta P}{\Delta P} \frac{\sqrt{k} \rho}{\mu} \frac{v_y^2 m^2 (R^2 - r^2)^2}{R^4}.
\]

In this case, the linear parameter of the inductive component of the flow is part of the dimensionless component \(\beta = L_o / L_f\), when the inductive load is in the ratio \(L_i = \frac{1}{p(t)} \int Q dt\), when \(p(t)\) and \(Q(t)\) - changes
in reservoir pressure and production well rate, respectively. At the same time, the number of dimensionless quantities in the most complete form is determined taking into account piezo capacitances.

**Calculation of the values of piezoelectric capacitance of the RFC.** When deriving the hydraulic hydraulic piezo capacitance, total porosity coefficient \( m \) is used in the form of the ratio of the linear volume of total voids \( V_r \) to the total linear volume of rock specimen \( V_n \). Then, for the hydraulic piezo-capacitance, \( C_h = V_r / \sigma_f m \), where \( \sigma_f \) is fluid saturation of porous media. Using this ratio in the characteristic of porosity \( m \) for the modified Bernoulli equation (2), the ratio is set in the filtration velocity

\[
v_f = v_0 \left(1 - \frac{r^2}{R^2}\right) m = v_0 \left(1 - \frac{r^2}{R^2}\right) \frac{\sigma_f V_n}{C_h}.
\]

The filtration rate for the linear term of the Dupuy-Forchheimer equation (1) is

\[
v_f = \frac{(\Delta P k)}{(\Delta L \mu)}.
\]

Multiplying the numerator and denominator of equation (9) by porosity coefficient \( m \) and equating it to equation (10), we get the following relation

\[
v_0 \left(1 - \frac{r^2}{R^2}\right) \frac{\sigma_f V_n m}{V_r m} = \frac{\Delta P}{\Delta L} \frac{k V_n}{\mu m v_0} \frac{R^2}{(R^2 - r^2)}.
\]

Based on expression (12), we obtain the numerical expression of the dimensionless capacitance for the RFC \( \tilde{\gamma} = C_{d_h} / C_h \), where \( C_{d_h} \) is capacity of the perforation interval of the water-injection well and the fracture of the RFC in the direction to the production well. The obtained numerical values of the linear parameters of the RFC determine complex dimensionless values.

**3. Results and discussion**

In the above equation, the dimensionless time is in the ratio \( \tau = t / \sqrt{\frac{L}{\mathcal{C}}} \), and the natural frequency is determined as a functional of real frequency \( F \) as \( \omega = F / \sqrt{\frac{L}{\mathcal{C}}} \). Based on this numerical simulation for the previously obtained minimum values of resistive loads \( R_{00} \), the boundaries of the previously found equation are

\[
\ctg(\omega_0) = \omega_0 \tilde{\gamma} \quad \text{(for } R_0 \rightarrow \text{min)},
\]

(13)

when calculating natural frequencies of the RFC when switching the maximum values of active resistances \( (R_{\omega_0}) \) of the flows of liquid in the production well

\[
\tg(\omega_0) = -\omega_0 \tilde{\gamma} \quad \text{(for } R_{\omega_0} \rightarrow \text{max}).
\]

(14)

Figure 1 shows the combined graphs of the dependences of functionals \( F_{i1} = \ctg(\omega_0) \) and \( F_{i2} = \omega_0 \) for the upper half-plane, and \( F_{i2} = \tg(\omega_0) \) and \( F_{i2} = -\omega_0 \) for the lower half-plane. Various functions for finding the natural frequencies of the RFC are determined by the areas of intersection of different sections of trigonometric functions [7] and linear segments. This is due to the variation of the parameters \( R_h, L_h \) and \( C_h \) for the trajectories of the RFC within the interacting wells.
**Figure 1.** The graph of combined functions for selecting resonant frequencies of a system with active loads.

When the RFC functions with an inductive load, the equation for RFC conversion determines natural frequencies by intersection areas of various functions $F$ in the form

$$
\operatorname{tg}(\omega_i) = \frac{(1 - \beta \gamma \omega_i^2)}{\omega_i (\beta + \gamma)}. 
$$

(15)

Figure 2 shows the graphs of trigonometric functions $F = \operatorname{tg}(\omega_i)$ and lines $F = (1 - \beta \gamma \omega_i^2) / \omega_i (\beta + \gamma)$.

In the above equation, natural frequencies of the RFC frequencies with inductive load $L_i$ are determined similarly to the above dependencies.

**Figure 2.** The graph of functions for selecting resonant frequencies of an inductive load system

4. **Conclusion**

1. The Dupuis-Forchheimer and Bernoulli ratios found for the RFC is an effective tool for calculating the volumes of tracer tags and tamponage under increased delivery pressure to the required coordinate along the channel with fictitious radius $R$ under the hard operation mode.

2. Analysis of the parameters of the hard mode in the RFC with fictitious radius $R$ and the elastic water-pressure mode with reduced radius $r$ can predict the FCPs.

3. Quality of oil displacement with plugging of worn RFC sections at coordinate-discontinuous controls with software-defined time units, reservoir pressures and filtration rates are improved through timely monitoring of its FCPs.

4. Quality of oil displacement is improved by adjusting resonant frequencies of the RFC with inductive load of low watered oil of production wells and resistive loads of highly watered oil under discontinuous formation control.

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