Numerical 3D simulation of enhanced oil recovery methods for high-viscosity oil field

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Abstract. The paper is devoted to the numerical simulation of oil recovery process using the technologies of polymer flooding and surfactants. The simulation is performed on the basis of the finite element method as well as the special scheme of flow balancing and phase flows between the cells, which along with high accuracy of pressure approximation, ensures the conservation of mass of filtering mixture components. The possibilities of simulation of different mechanisms of interaction of injected compositions with a medium are presented. The results of numerical simulation of different reservoir stimulations are shown using the digital model of the high-viscosity oil field in Tatarstan. It is shown that the application of polymer flooding and surfactant-polymer solutions makes it possible to increase the oil fraction in the produced fluid and, consequently, enhance the oil recovery.

1. Introduction
In order to enhance high-viscosity oil recovery, the technologies based on the application of high viscosity compositions are used [1]. In this connection, it is important to design the field development. For this purpose, the numerical simulation of the multiphase filtration is widely used [2–10].

Commercial software packages (most of them are mentioned in [10]) are based on the mathematical models [3] and various modifications of the finite difference method (FDM). Unlike the FDM, the finite element method (FEM) allows reasonably accurate description of wells and curvilinear surfaces between the layers, the local increase of the basic functions order (for example, in wells vicinities), and application of the non-conforming finite element mesh [11] (for example, in order to include local inhomogeneities into the computational domain). However, due to the fact that the formal application of the FEM does not guarantee the conservation of mass of filtering mixture components, some modern approaches are based on the hybrid finite element – finite volume method [5–7]. The approach considered in this paper is based on the FEM and special scheme of flow balancing [12], which ensures the conservation of mass of filtering mixture components.

In the technologies of the enhanced oil recovery, different compositions can be applied. These compositions can be characterized by different mechanisms of interaction with a medium (geological formation and fluid). These mechanisms are studied, as a rule, in laboratory conditions. However, the effectiveness of their application can be estimated using the digital model of the specific oil field for which further development is designed. Naturally, this digital model must be adequate, and numerical methods should allow taking into account different mechanisms of interaction with a medium, i.e. makes it possible to simulate multiphase filtration taking into account the mass fraction of the components of
filtering phases, rules of their interaction, possible transition of components from one phase to the other as well as possible formation of new phases, which can have their own values of viscosity and/or relative permeability different from other phases. Therefore, water, oil, emulsion, immiscible polymer solutions, etc. can be a separate phase.

In this paper, we present the results of simulation of reservoir stimulation by high-viscosity agents using the digital model of the high-viscosity oil field in Tatarstan.

2. The mathematical models used for multiphase filtration calculation

Taking into account the specifics of the considered oil field (very low gas concentration), we use the multiphase filtration model for the case of incompressible and isothermal fluid [8, 9].

The field of the pressure \( P \) at each time instant can be obtained from the solution of the partial differential equation

\[
-\text{div} \left( \sum_{m=1}^{M} K^m \frac{\eta^m}{\eta^m} \text{grad} \left( P + P_c^m \right) \right) = f
\]

with boundary conditions

\[
P|_{\Gamma_1} = P_s,
\]

\[
\sum_{m=1}^{M} K^m \frac{\eta^m}{\eta^m} \frac{\partial P}{\partial n}_{\Gamma_2} = 0.
\]

Equations (1)–(3) use the following notifications: \( f \) is the function describing the withdrawal or injection of mixture as well as the change of the mixture volume caused by chemical reactions, \( K \) is the tensor of absolute permeability, \( m \) is the number of the phase, which is characterized by the relative permeability \( K^m \), the viscosity \( \eta^m \), and capillary pressure \( P_c^m \), and \( \Gamma_1, \Gamma_2 \) are the sets of remote and isolated boundaries of the computational domain \( \Omega \), respectively.

We assume that the porosity \( \Phi \) and the tensor of absolute permeability \( K \) are time-independent piecewise constant functions in space, and at any time instant the pores of a medium are fully filled with a multi-phase mixture.

Each \( m \)-th phase can consist of \( L^m \) component and, besides the parameters mentioned above, is characterized by the saturation \( S^m \), density \( \rho^m \) and set of values \( \chi^m_l \) defining the mass fraction of the \( l \)-th component in the \( m \)-th phase.

The boundary problem (1)–(3) is solved by the finite element method on the non-conforming meshes with hexahedral cells.

Making use of the pressure field distribution, we calculate the flowing mixture volumes as

\[
V = \left[ \int_{\Omega} \left( \sum_{m=1}^{M} K^m \frac{\eta^m}{\eta^m} \text{grad} \left( P + P_c^m \right) \right) \cdot \hat{n} \, d\Gamma \right] \Delta t
\]

where \( \Delta t \) is a time step, \( \hat{n} \) is the outward normal to the finite element boundary. In order to ensure the conservation of mass of filtering mixture components, we use the special method of the flow balancing proposed in [12].

On the basis of the mixture volumes \( V_{\Omega, \Delta t} \) flowing from the cell \( \Omega_{k_i} \) to the cell \( \Omega_{k_j} \) through the face \( \Gamma_1 \), new values of saturations are calculated as
\[ S_{\text{new}}^{m} = \frac{\text{mes}(\Omega_e)\Phi S^{\infty} + V_{\text{in}}^{m} - V_{\text{out}}^{m}}{\text{mes}(\Omega_e)\Phi} \]  

(5)

where \(\text{mes}(\Omega_e)\) is the cell volume, and \(V_{\text{in}}^{m}\) and \(V_{\text{out}}^{m}\) are the volumes flowing into and out of \(\Omega_e\). These volumes, in their turn, for each face \(\Gamma_j\) of the cell \(\Omega_e\) are defined by the ratio

\[ V_{\Gamma_j,\Omega_e}^{m} = V_{\Gamma_j,\Omega_e} \cdot \frac{\kappa^{m}}{\eta^{m} \sum_{i=1}^{M} \kappa^{i} / \eta^{i}}. \]  

(6)

New values of the mass fraction \(x_{\text{new}}^{lm}\) are calculated by the equation

\[ x_{\text{new}}^{lm} = \left(n_{\Omega_e}^{lm} \cdot M_{l}\right) / \left(\sum_{k=1}^{C} n_{\Omega_e}^{km} \cdot M_{k}\right). \]  

(7)

In equation (7), \(M_{l}\) is the molar mass of the component \(l\), and \(n_{\Omega_e}^{lm}\) is the number of moles of the substance in the cell \(\Omega_e\), which can be found by the ratio:

\[ n_{\Omega_e}^{lm} = \sum_{j=I_{\Omega_e}}^{C} \rho_{\Omega_e}^{lm} \chi_{\Omega_e}^{lm} V_{\Gamma_j,\Omega_e}^{m} / M_{l} + \rho_{\Omega_e}^{lm} \chi_{\Omega_e}^{lm} \left(V_{\Omega_e}^{m} - \sum_{j=I_{\Omega_e}}^{C} V_{\Gamma_j,\Omega_e}^{m}\right) / M_{l}, \]  

(8)

where \(\Omega_{\Omega_e}\) is the finite element from which the mixture volume \(V_{\Gamma_j,\Omega_e}^{m}\) flows into the cell \(\Omega_e\) through the face \(\Gamma_j\), \(I_{\Omega_e,\Omega_e}\) and \(I_{\text{out},\Omega_e}\) are the sets of the global face numbers corresponding to the phase volumes flowing into and out of \(\Omega_e\), and \(V_{\Omega_e}^{m}\) is the volume of the phase \(m\) in the cell.

In order to define the chemical reaction, we use two sets of number pairs \((l, m)\in I_{\text{ch},1}^{2}\) and \((i, k)\in I_{\text{ch},2}^{2}\), which designate the numbers of the components and phases of the reacting substances and substances obtained as a result of the reaction, respectively. For each number pair, we preset the value \(n_{rs}\), corresponding to the quantity of reacting moles of the component \(r\) in the phase \(s\). Besides, we preset the reaction rate defined in terms of the amount of one of the reacting substances per unit time.

In order to simulate a chemical reaction in the cell \(\Omega_e\), the current time interval \(\Delta t\) is divided into the subintervals \(\tau\), and the quantity of moles \(\tilde{n}_{\Omega_e}^{lm}\) reacting in a time \(\tau\) is calculated

\[ \tilde{n}_{\Omega_e}^{lm} = \rho_{\Omega_e}^{lm} \chi_{\Omega_e}^{lm} V_{m} \cdot \nu \cdot \tau, \]  

(9)

where the rate \(\nu\) is defined in terms of the substance corresponding to the component \(l\) in the phase \(m\).

On the basis of the values \(\tilde{n}_{\Omega_e}^{lm}\) and \(n_{lm}\), the molar quantity of other substances reacting and obtained as a result of the reaction in a time \(\tau\) in the cell \(\Omega_e\) are defined.

Then, new mass fractions of reacting and obtained substances are calculated in the form
New values of the molar quantities are calculated as $\chi_{\Omega}^{lm} = \left( n_{\Omega}^{lm} \cdot M_{l} \right) - \left( \tilde{n}_{\Omega}^{lm} \cdot M_{l} \right)$, $(l,m) \in I_{\omega,1}^{2}$.

Using new values of mass fractions, we calculate new values of densities on the basis of which, in their turn, new volumes of phases are defined.

Before the pressure calculation at the next global time step, new values of saturations, relative permeabilities, and viscosities for all phases as well as the change of the mixture volume appearing as a result of chemical reactions are calculated.

The numerical method presented is implemented in the software with a graphical user interface (GUI).

### 3. Numerical simulation results

#### 3.1. Verification

In order to verify the software, we use the results of the 10th SPE Comparative Solution Project [10]. The model dimensions are 1,200×2,200×170 ft$^3$. The distributions of porosity and tensor components of absolute permeability are set on the grid containing 60×220×85 cells. The porosity distribution is shown in Figure 1 (the screenshot of the GUI software developed). The injection well (I1) is placed in the domain center and has an injection rate of 5,000 B/D. The four producing wells (P1-P4) are placed in the corners and produce at 4,000 psi bottomhole pressure.

Figure 2 shows the water cut curves obtained with the use of our software (the black curves with labels) in comparison with Landmark (red curves) and Roxar (green curves) solutions.

Figure 3 shows the oil rate curves obtained with the use of our software (the black curves with labels) in comparison with Landmark (red curves) and Roxar (green curves) solutions.

**Figure 1.** The distribution of porosity (the screenshot of the GUI software developed).
Figure 2. The water cut curves: our (the black curves with labels), Landmark (red curves), and Roxar (green curves) solutions.

Figure 3. The oil rate curves: our (the black curves with labels), Landmark (red curves), and Roxar (green curves) solutions.

As seen from these Figures, our curves are either between the curves obtained by the use of other codes or quite close to one of them (or to both if they are close to one another).

3.2. Numerical simulation of reservoir stimulations

We simulate the injection of displacement agents using the geological model which is constructed on the basis of the historical well data observed on one of the high-viscosity oil field in Tatarstan. The initial distributions of the oil saturation and absolute permeability are shown in Figure 4. The total number of wells used in simulation is 61. Of them three wells were used only for injection, and fifteen wells were firstly used for exploitation and then, at different time instants, they became injection wells. Other wells were used for exploitation within the whole time interval. The whole time interval of simulation is 12000 days. Most of the wells contain several perforations which are made and abandoned at different time instants, i.e. injection or production for these wells is performed in different layers. The data on injection and production flow rates as well as the time instants of making and abandoning perforations are taken from the historical data. The injection of displacement agents is carried out in two wells (see wells designated by 1 and 2 in Figure 5).

We consider three variants. In the first variant, we assume that only water is injected. In the second variant, the polymer solution is injected into the wells during a year, after that water is injected again. The third variant differs from the second one in that instead of the polymer solution, the surfactant-polymer solution is injected.

The polymer solution moving in the reservoir mixes with the reservoir and injected water and, as a result, the solution viscosity reduces proportionally to the decrease of the polymer concentration.

In order to simulate the injection of the surfactant, different mechanisms of its interaction with a medium are considered. The first mechanism is as follows. When the surfactant enters the cell, it changes the property of the formation to retain oil (i.e. residual oil saturation).

The results of simulation for the variant in which the surfactant-polymer solution is injected into the wells 1 and 2 are shown in Figure 5. They show that the surfactant is gradually transferred (figures in the centre) with continuous reduction of its concentration (nonaxisymmetric distribution of the surfactant density is caused by the fact that during its injection, all wells of the oil field produce or inject; this leads to a complex distribution of flows). The right figures show the change of the property of the formation to retain oil. Before the formation interacts with the surfactant, its retention level is 0.3 (red color). If the surfactant concentration in the cell is sufficient, this level reduces to 0.1 (white color). The
left figures show the "washing" residual oil with its displacement by the high-viscosity composition as evidenced by the increase in oil saturation (red rings) around light ("washed") zones.

Figure 4. In-layer distributions of the initial oil saturation (on the left) and absolute permeability (on the right).

Special attention should be paid to the following. As seen from the distributions presented in Figure 5, approximately the same situation is in all three layers in the vicinity of well 1. It is related to the fact that all three layers are almost homogeneously oil saturated in this zone. The injection into well 2 is performed only in the top layer. The layer which follows the top layer has low permeability and contacts with the water-bearing layer. Therefore, the situation in layers in this zone differs greatly. Besides, the central figures show that near well 1, the surfactant is weakly transferred to the north. It is related to the fact that low permeability "wall" in the digital model lies near well 1.

Figure 6 shows oil saturation distributions for all three variants considered above.
Results presented in the figure show that when the polymer solution is injected, the portion of oil is concentrated at some distance from the injection wells (red rings surround zones around these wells), but these zones around wells contain the residual oil. If the surfactant-polymer solution is injected, the oil is also concentrated at some distance, and the residual oil is "washed" from the zones near the wells (the corresponding zones around the injection wells are lighter).

The second variant of the interaction mechanism of the surfactant with the medium is as follows. The surfactant entering a cell is combined with oil in the following proportion: 0.024 moles of surfactant and 1 moles of oil. As a result, a new "combined oil" phase in which surfactant and oil are included in the same proportion is formed. The residual saturation of this phase either significantly decreases or equals the zero.

For this variant of simulation, Figure 7 shows in-layer distributions of the surfactant density and the saturation of the "combined oil" with a different value of residual saturation. The distributions are presented at two time instants. As seen from the distribution presented in Figures 7b,c the "combined oil" phase is transferred from injecting to producing wells. The analysis of saturation distributions of oil in the "oil" phase (this is the oil without surfactant) shows that near the injecting wells, white sub-domains appear (similar to Figure 6c). This indicates that at least the portion of the "combined oil" is obtained from the residual oil (and, therefore, as in the previous case, the residual oil is "washed").
Figure 7. In-layer distributions of the surfactant density (a) and the saturations of the "combined oil" with the residual saturation equal to the zero (b) and 0.1 (c) at two time instants.

Figure 8 shows the oil fraction in the produced fluid for all three variants: water injection (green color), polymer solution injection followed by water injection (dark blue color), and injection of surfactant-polymer solution followed by water injection. The latter variant, in its turn, is presented for two interaction mechanisms of surfactant with the medium: the change of the property of the formation to retain oil (red color) and formation of a new "combined oil" phase (black color curve with labels). The portion of oil, which "comes to" the producing well in the "combined oil" phase, is shown by black color without labels.
Figure 8. The oil fraction in the produced fluid for three variants: water injection (green color), polymer solution injection followed by water injection (dark blue color), and injection of surfactant-polymer solution followed by water injection (red and black colors, see text for more details).

On the basis of results obtained we can conclude the following. The application of the polymer and surfactant-polymer solutions at the later stage of oil field development makes it possible to increase the oil fraction in the produced fluid. Moreover, additional investigations show that the polymer solution application makes sense at more early stages of oil field development. This allows significant enhancement of high-viscosity oil recovery. The simulation results show that the considered interaction mechanisms of surfactants with a medium give similar effects, but the time delay for these effects is still more than for the effects of polymer solution application.

4. Conclusion
In general, the simulation methods presented enable us to study the possibilities of the application of various displacement agents and their compositions in order to enhance high-viscosity oil recovery and design further development of the oil field on the basis of its digital hydrodynamic model. The specifics of interaction mechanisms of compositions with a medium should be preliminary studied in laboratory conditions.

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