Design of i-Fields System Component: Computer Model of Oil-Recovery by Polymer Flooding

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Abstract: This article describes the issues and approaches the design and development of distributed high-performance system for analysis of oil fields within the i-fields (smart fields) concept. The system is based on hydrodynamic model of collaborative filtering of oil, water, gas, polymer solution and the surfactant, taking into account influence of temperature. Built a 3D numerical parallel algorithm and web-based platform for data analysis and calculation on a supercomputer. Obtained distribution of the main technological parameters: distribution of pressure, saturation of each phase, the concentration of surfactant and polymer, and temperature.

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1 INTRODUCTION

Nowadays there are many approaches to develop software systems for the analysis and development of oil and gas fields (software.slb.com, rfdyn.com). But the problem of creating fields monitoring systems in real-time, modelling and optimal control of field development began to appear only in recent years due to the development of information technologies. Particularly interesting approach for the development of information systems - smart fields, i-fields, e-fields and other. These systems are mainly aimed at solving problems of "continuous" optimize of operations on oil field: location, quantity, and planning new wells. For the implementation of such advanced technologies in large and complex oil and gas fields require detailed research data on the methods of drilling / plug wells (horizontal, inclined and multilateral), with sensors (pressure, inflow, temperature, etc.) in the borehole

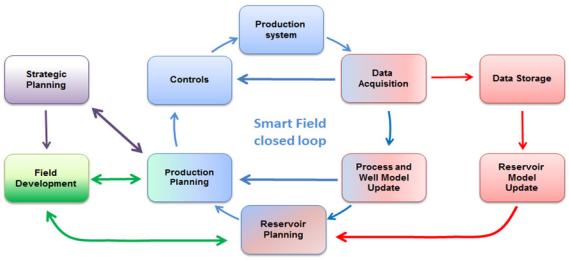

Figure 1: A “Closed-loop intelligent field” scheme (Smart Fields Consortium, Stanford University, USA).

geophysical measurements. In this case, there is an acute demand for the need of modelling and monitoring in real time to aid decision making and optimal management/exploitation involving the latest equipment and hardware/software systems.

Synthesis of the above, in the form of implementation of the "closed-loop intelligent (smart) field" is shown in Figure 1 (smartfields.stanford.edu). As can be seen in the figure, the cycle consists of two basic components: planning / forecasting and modeling processes into reservoir on oil field. In this paper, we consider it is the second component. Within the framework of implementation of these components, project authors will design and develop distributed high-performance analysis system of oil and gas fields within i-fields concept with modern mathematical models of three-phase flow in porous media and computational algorithms with three-dimensional visualization of data to monitor them in real time.

Surfactant and polymer flooding are the effective chemical EOR methods. There are various interactions between the surfactant and the reservoir fluids, such as adsorption, interfacial tension, wettability (Babalyan, 1983). Surfactants are used to reduce the interfacial tension between crude oil and reservoir water and increase the mobility of "trapped" oil in the pore space. Polymer injection method is used to reduce water mobility and increase water viscosity. Decreasing the permeability of the water phase increases flooding

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efficiency and significantly improves quality of displacement (Lake, 1989; Sorbie, 1991). The paper Imankulov, 2014 describe the problem of oil displacement process by polymer injection, and compares the results of numerical experiments using gellan and polyacrylamide, a change in viscosity of the aqueous phase is taken as a linear function and does not depend on temperature.

At present, the combined methods of enhanced oil recovery are used. One such method is surfactant flooding in combination with water soluble polymers. Surfactant and polymer are injected into the reservoir, then, push oil to the production wells by pumping water. This method shows higher recovery rate comparing with using surfactant and polymer alone (Fathaddin, 2011; Rai, 2013).

This work aims to study the mathematical model of oil displacement by polymer-surfactant flooding, which is considers the influence of temperature effects and dependence of polymer/surfactant solution viscosity on agents concentration and water salinity. Development of sequential/parallel computational algorithm for solution of 3D problem using MPI and CUDA technologies.

2 MATHEMATICAL MODEL

2.1 Mathematical Model of Polymer and Surfactant Flooding

Several physical and chemical processes influence the properties of the polymer/surfactant and polymer/surfactant solution. For example, viscosity of injected solution depends on various factors, such as reservoir temperature, concentration of polymer/surfactant in solution and water salinity and etc. The model considers following assumptions:

- the porous media and fluid are incompressible;
- gravitational forces are not taken into account;
- the two-phase flow (aqueous, oleic) is subject of the Darcy's law;
- water, polymer, surfactant and salt are fully mixed;
- adsorption of the polymer affects only on the relative permeability of the aqueous phase;
- dissolution of polymer and surfactant in oil is very small.

Based on the above assumptions, we can write the mathematical model of two-phase flow in porous media.

Mass conservation equation for aqueous and oleic phases (Akhmed-Zaki, 2012) is:

$$m\frac{\partial S_w}{\partial t} + div(\vec{v}_w) = q_1 \quad (1)$$

$$m\frac{\partial S_o}{\partial t} + div(\vec{v}_o) = q_2 \quad (2)$$

$$S_w + S_o = 1$$

where m – porosity, S_w, S_o–water and oil saturations, q_1, q_1 - source or sink, $\vec{v}_w, \vec{v}_o$ – velocity of the water and oil phases, which is expressed by the following law:

$$\vec{v}_i = -K_0\frac{f_i(s)}{\mu_i}\nabla P, \;\; i = w, o \quad (3)$$

$f_i(s), \mu_i$ – relative permeability and viscosity of fluids, K_0 – absolute permeability.

Polymer and surfactant concentration and salt transport equations can be written as (Babalyan, 1983):

$$m\frac{\partial}{\partial t}(c_p s_w) + \frac{\partial a_p}{\partial t} + div(v_w c_p) = div(mD_{pw}s_w\nabla c_p) \quad (4)$$

$$m\frac{\partial}{\partial t}(c_{sw}s_w + c_{so}s_o) + \frac{\partial a_{surf}}{\partial t} + div(v_w c_{sw} + v_o c_s = div(mD_{sw}s_w\nabla c_{sw} + mD_{so}s_o\nabla c_{so}) \quad (5)$$

$$m\frac{\partial}{\partial t}(c_s s_w) + div(v_w c_s) = 0 \quad (6)$$

where c_p, c_s – polymer and salt concentrations in aqueous phase, $c_{sw,}\, c_{so}$ – surfactant concentration in aqueous and oleic phases, a_p, a_{surf} – polymer and surfactant adsorption functions, D_{pw}, D_{sw}, D_{so} – polymer and surfactant coefficients.

Heat transfer equation:

$$\frac{\partial}{\partial t}[(1-m)\boldsymbol{C}_r\rho_r + m(\boldsymbol{C}_w s_w\rho_w + \boldsymbol{C}_o s_o\rho_o)T] + div(\rho_w\boldsymbol{C}_w v_w) + div(\rho_o\boldsymbol{C}_o v_o) = div[((1-m)\lambda_0 + m(\lambda_1 s_w + \lambda_2 s_o))\nabla T] \quad (7)$$

where $\boldsymbol{C}_w, \boldsymbol{C}_o, \boldsymbol{C}_r$ – specific heat of water, oil and rock, ρ_w, ρ_o, ρ_r – density of water, oil and rock, $\lambda_0, \lambda_1, \lambda_2$ – coefficients of thermal conductivity.

Flory-Huggins equation can represent a mathematical relation which describes the dependence of water phase viscosity on concentration of salt, surfactant and polymer. This dependence, which takes into account temperature changes can be written as (Flory, 1953):

$$\mu_a = \mu_w[1 + (\gamma_1 c_p + \gamma_2 c_p^2 + \gamma_3 c_{sw} + \gamma_4 c_{sw}^2)c_s^{\gamma_5} - \gamma_6(T - T_p)] \quad (8)$$

$$\mu_o = \mu o_o[1 - \gamma_7(T - T_p)] \quad (9)$$

where $\gamma_1, \gamma_2, \gamma_3, \gamma_4, \gamma_5, \gamma_6, \gamma_7$ – nondimensional constants. μo_o – initial viscosity of oelic phase, T_p – reservoir temperature.

Relative permeability curves are taken as follows:

$$f_w(S_w) = S_w^{3.5};\ f_o(S_w) = (1 - S_w)^{3.5}$$

The type of the polymer and surfactant determines their adsorptions degree. Langmuir's law can represent the relation between adsorbed polymer/surfactant and polymer/surfactant concentration in the solution (Babalyan, 1983):

$$a = \frac{bc_p}{1 + bc_p}$$

where b – Langmuir's constant.

Permeability reduction factor R_k can be described as follows (Wegner, 2012):

$R_k = 1 + (R_{RF} - 1)a$

R_{RF}- residual reduction factor.

Initial and boundary conditions are:

$$\begin{aligned} &s_w|_{t=0} = s_{w0}, \\ &c_{pw}|_{t=0} = c_{p0},\ a_p|_{t=0} = a_{p0}, \\ &c_{sw}|_{t=0} = c_{sw0},\ c_{so}|_{t=0} = c_{so0}, \\ &a_{surf0}|_{t=0} = a_{surf0} \end{aligned} \quad (10)$$

$c_s|_{t=0} = c_{s0}$

$T|_{t=0} = T_p$

$$\begin{aligned} &\frac{\partial s_w}{\partial n}\Big|_{\partial\Omega} = 0;\ \frac{\partial P}{\partial n}\Big|_{\partial\Omega} = \gamma \cdot V_p;\ \frac{\partial T}{\partial n}\Big|_{\partial\Omega} = \gamma \cdot V_t; \\ &-D\frac{\partial c_{pw}}{\partial n} + \vec{v}_{1n} \cdot c_{pw}\Big|_{\partial\Omega} = q_n \cdot \tilde{c}_{pw}; \\ &-D\frac{\partial c_{sw}}{\partial n} + \vec{v}_{1n} \cdot c_{sw}\Big|_{\partial\Omega} = q_n \cdot \tilde{c}_{sw}; \\ &\frac{\partial c_s}{\partial n} + \vec{v}_{1n} \cdot c_s\Big|_{\partial\Omega} = 0; \end{aligned} \quad (11)$$

Pressure equation obtained is by adding (1) and (2):

$$div(\vec{v}_w) + div(\vec{v}_o) = 0 \quad (12)$$

Correctness of the proposed model was confirmed by two stages of verification (Imankulov, 2014):

- comparison of numerical results with laboratory experiments;
- and with results of calculations on hydrodynamic simulator Eclipse 100.

2.2 Numerical Method

For numerical calculation, consistency of units and order of variables are important. Therefore, a system of equations (1) - (12) is converted to a dimensionless form. To solve these equations, an explicit scheme is used (Samarskii, 1989). First of all, fluid properties and physical parameters of reservoir are set. Further calculations are conducted in the following order:

- distribution of pressure;
- saturation (by the known distribution of pressure);
- distribution of salt, surfactant and polymer concentrations;
- distribution of temperature in the reservoir;
- aqueous phase viscosity, depending on salt, surfactant and polymer concentrations is recalculated;
- aqueous phase permeability considering the polymer adsorption is recalculated.

The results of numerical calculations for non-isothermal oil displacement are shown in the following Figures 2-7.

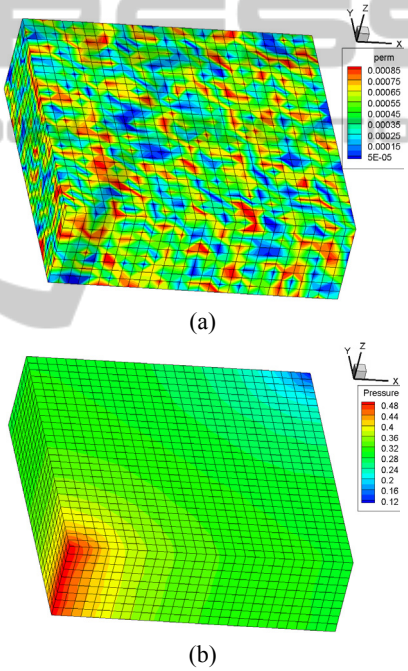

Figure 2: (a) Permeability field; (b) distribution of pressure.

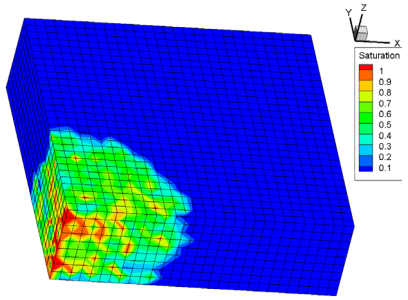

Figure 3: Distribution of water saturation at different moments of iteration times.

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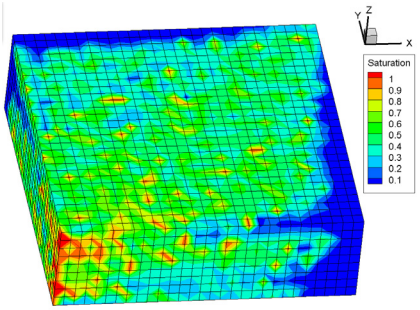


Figure 3: Distribution of water saturation at different moments of iteration times (cont.).

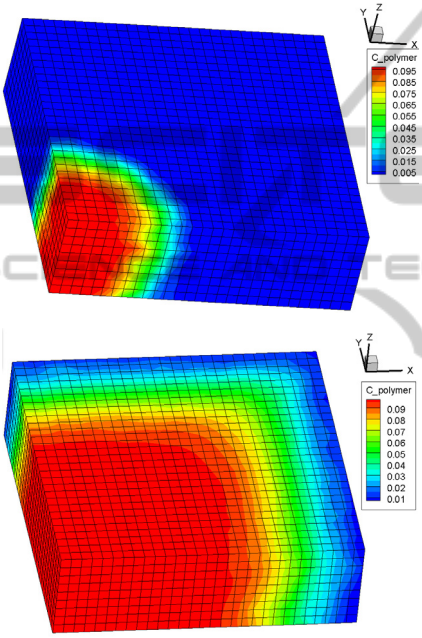


Figure 4: Distribution of the polymer concentration in the aqueous phase at different moments of iteration time.

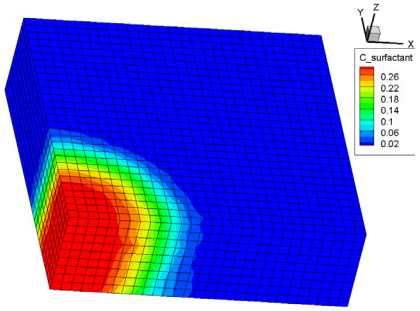


Figure 5: The distribution of the surfactant concentration in the aqueous phase at different moments of iteration times.

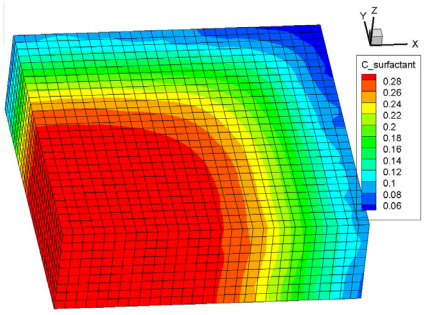


Figure 5: The distribution of the surfactant concentration in the aqueous phase at different moments of iteration times(cont.).

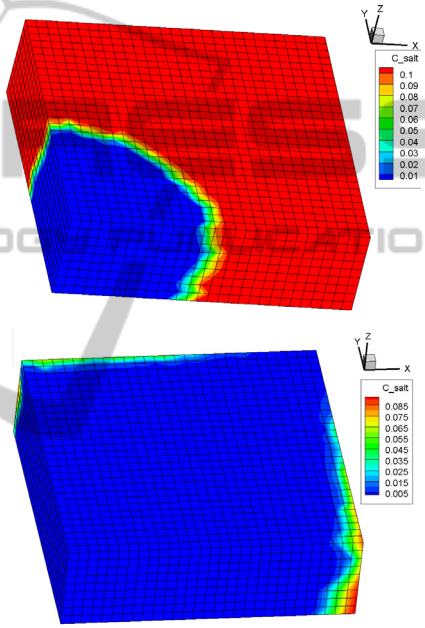


Figure 6: Distribution of the salt concentration in the aqueous phase at different moments of iteration times.

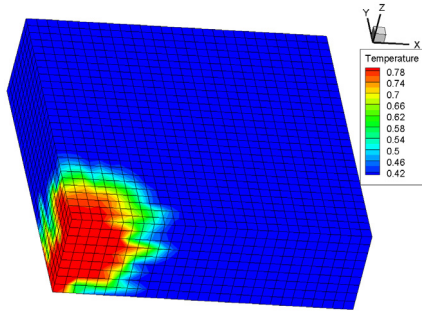


Figure 7: The temperature distribution at different moments of iteration times.

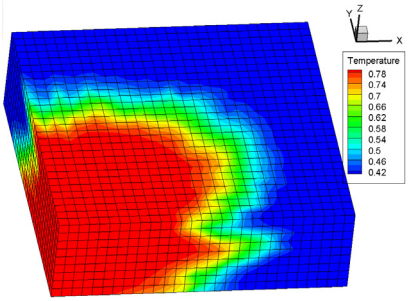


Figure 7: The temperature distribution at different moments of iteration times (cont.).

For parallelization of this algorithm, the computational domain is divided into partially overlapping subdomains, calculations in which are performed independently of each other. After each iteration, it is necessary to make the exchange of data at the boundaries of the subdomains (Matkerim, 2013). The above method was implemented using MPI technology.

The speedup and efficiency of parallel algorithm on the 64x64x64, 64x128x128, 64x256x256, 64x512x512 grids are investigated.

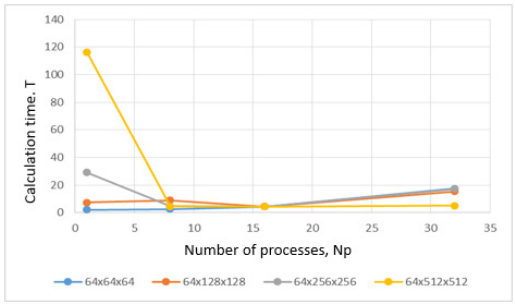
Speedup of parallel algorithm is estimated as the ratio computing time on a single processor T_1 to computing time on p processors T_p:

$$S_p = \frac{T_1}{T_p}$$

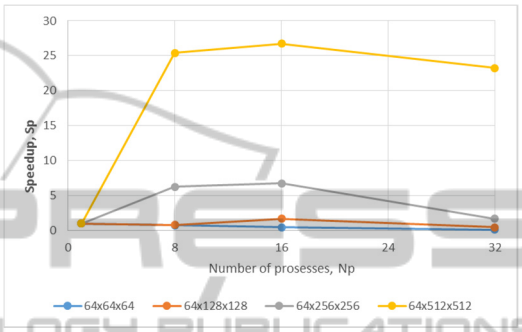
the efficiency of parallel algorithm is estimated as ratio of speedup to the number of processors p:

$$E_p = \frac{S_p}{p}$$

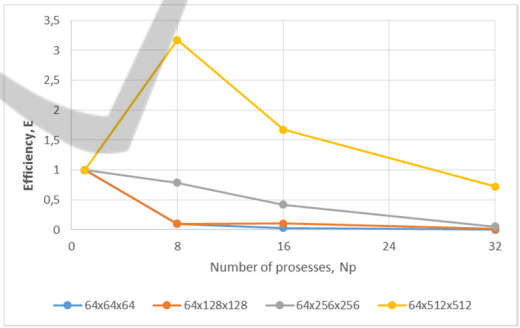
As you can see from Figure 8, the computing time of serial code very large in comparison with the parallel code at large computational grids. Also, you will notice that, when the number of processes exceeds 16, speedup and efficiency of the algorithm decreases. This is because an increase in the number of processes is increases number of data exchanges between processes. Therefore, the computing time increases, since these exchanges are also takes time. Accordingly, we can see that high efficiency can only be achieved on large grids, as on such grids loss of time on data exchanges between processes are not significant.



(a)



(b)



(c)

Figure 8: (a) Calculation Time, Speedup (B) and Efficiency (C) of Parallel Algorithm for Different Grid Sizes and on Different Process Numbers.

2.3 3D Web Hydrodynamic Simulator

The system represents interactive package for analysis and estimation of technological problems of hydrodynamic simulation of oil and gas fields. The basis of the produced program complex the modern scientific developments which allow to use heterogeneous multiprocessing computer facilities at their limit. Because of this it is possible to demonstrate high efficiency of calculations. The system is initially developed as an interactive package - Web applications on the basis of client-server architecture models of MVC – Model View Controller type. The possibility of automatic connection and start of calculations on a

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supercomputer is presented. The user can observe calculation results in real-time, manage calculation process and also modify model online.

Visualization module of three-dimensional reservoir loads the data from special format text files, reads geological model from them and provides visualization of this model in the form of three-dimensional contour.

The visualization module is presented in two ways:

1) As a desktop application which uses hardware resources of the client computer and is not integrated into the basic program. It is implemented using OpenGL graphics platform and C++ programming language (figure 9).

2) As a Web-module running on the server (supercomputer) and partially using hardware of graphics subsystem of client computer. Visualization is carried out on the basis of WebGL graphical technology, with JavaScript, HTML5 web-technologies (figure 10).

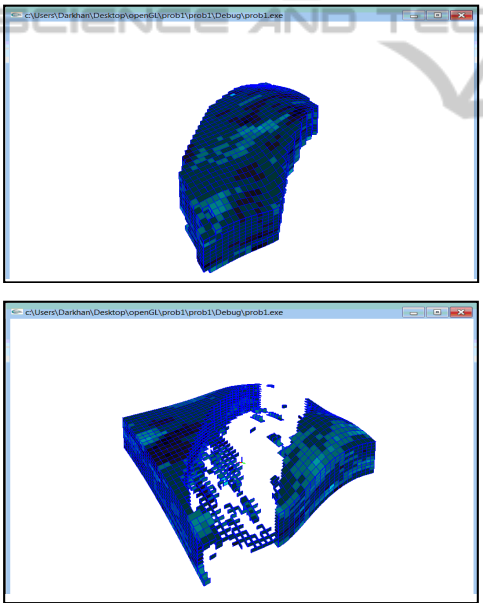
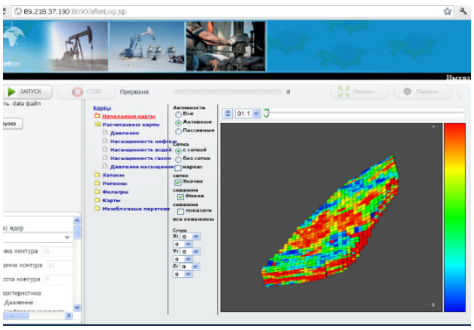
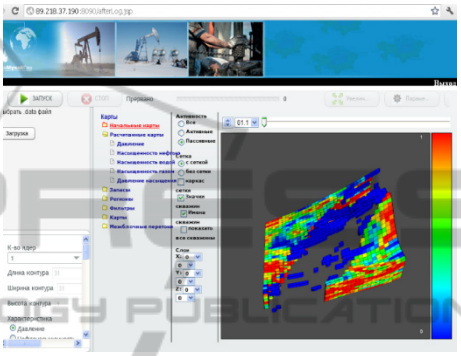


Figure 9: Desktop application, a) active and b) inactive blocks of field.



(a)



(b)

Figure 10: Web application, a) active and b) inactive blocks of field.

To automatically connect and run calculations on a supercomputer Java interface (MPJ-Express) with the support of a hybrid parallelization on OpenMP and MPI is developed.

3 CONCLUSIONS

A mathematical model of oil displacement process by polymer-surfactant injection is considered and solved, taking into account the dependence of solution viscosity on salt, surfactant and polymer concentrations and where viscosity of both phase are depends on temperature.

System of equations is solved using implicit/explicit methods and following numerical results were obtained: distribution of pressure, saturation distribution of both phases, salt, surfactant and polymer concentration and temperature distribution in reservoir.

The module of polymer injection analysis of distributed information system for analysis of oil field development with operational monitoring in real time and possibility of computing via remote access or Internet.

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Proposed simulator has ability to calculate on heterogeneous intercluster environment using special NumGrid software.

The polymer injection process into the oil reservoir for enhanced oil recovery can be modeled using proposed simulator. Presented results shows good consistence compared with results of the hydrodynamic simulator Eclipse (Black Oil).

If you do not use chemicals, you can provide little economic benefit. But the rejection of the development of such schemes does not lead to the desired oil recovery factor. On the one hand, increasing the concentration of chemicals leads to a non-linear increase of oil production, and on the other hand, increase the costs, because the used chemical reagents are not cheap. Consequently, it is necessary to choose the optimum concentration of reagents, for economic efficiency.

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