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Design of HPC System for Analysis the Gel-Polymer Flooding of Oil Fields

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Abstract

This article discusses development of the "Polymer flooding" module for distributed information system of oil fields development analysis. This module is designed to simulate displacement of oil using polymer injection method for

enhanced oil recovery and based on modern mathematical model that considers influence of salt and polymer concentrations on viscosity of injected reagent. Also, permeability changes of aqueous phase depending on adsorption of the polymer and residual resistance factor are considered. Results of numerical studies of two-dimensional and three-dimensional cylindrical domain are presented. Main results of numerical experiments compared with laboratory tests and calculations of reservoir simulator Eclipse (Blackoil). Distribution of main technological parameters is obtained and efficiency of oil displacement using polymer (polyacrylamide, gellan) injection is shown. The module of polymer injection of distributed information system for oil field development analysis (ISAR-2) with operational monitoring in real time is developed.

Keywords: EOR, polymer, gellan, Eclipse, adsorption, resistance factor, distributed system

1 Introduction

Polymer flooding – chemical enhanced oil recovery (EOR) widely used throughout the world. The technique of this method is following: added polymer reduces water mobility. Therefore, increase of viscosity and decrease of permeability at aqueous phase, increases efficiency of flooding and considerably improves quality of oil displacement [1]. However, several chemical and physical processes, carrying fluid flow, lead to loss of the polymer solution's viscosity. Viscosity of injected polymer solution can depend on several factors, such as polymer concentration, salinity of water and reservoir temperature [2, 3, 4].

In the papers [5, 6] experimental studies of oil displacement processes with gellan polymer conducted using cores of real oil fields in Kazakhstan. Laboratory experiments show that oil displacement ratio at injection of gellan solution is almost doubles water injection rate. Given paper aims to address following issues: study the mathematical model of oil displacement by polymer (gellan) injection considering dependence of polymer solution viscosity on concentration and salinity; development of the computational algorithm to solve given problem in cylindrical coordinates; comparison of numerical results with experimental results proposed in [5, 6] and calculations conducted in the hydrodynamic simulator Eclipse 100 (Blackoil).

2 Mathematical Model of Polymer Flooding

Generally, displacement of oil with polymer injection is influenced by complex physical and chemical processes, during simulation and numerical implementation of which some problems occur. The model considers following assumptions: fluid and porous media are incompressible; the model does not take into account the

capillary effects and gravitational forces; process is isothermal; two-phase flow is subject of the Darcy law; water, polymer and salt are completely mixed; adsorption of the polymer affects only on relative permeability of aqueous phase; dissolution of gellan in oil is very small.

Considering above assumptions, we can write equation of two-phase flow in the porous media which contains water and oil balance equation in the stream, the Darcy's law of motion, transport equation of polymer and salt in reservoir.

Equation of mass conservation for water and oil phases [7]:

$$m\frac{\partial S_w}{\partial t} + div(\vec{v}_w) = 0 \quad (1)$$

$$m\frac{\partial S_o}{\partial t} + div(\vec{v}_o) = 0 \quad (2)$$

$$S_w + S_o = 1$$

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

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

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

Equation for concentration distribution [8]:

$$m\frac{\partial}{\partial t}\left(c_p s_w\right) + \frac{\partial a}{\partial t} + div\left(v_w c_p\right) = div\left(D_w s_w \nabla c_p\right) \quad (4)$$

Equation for salt transport can be written as [8, 9]:

$$m\frac{\partial}{\partial t}(c_s s_w) + div(v_w c_s) = 0 \quad (5)$$

where c_p, c_s – polymer and salt concentration, a – polymer adsorption function.

In general, dependence of viscosity on the polymer and salt concentration is nonlinear. Figure 1 shows a significant increase in the viscosity of 0.2% gellan solution and reduction in viscosity of 0.2% PAAm solution at increase of salinity of the reservoir water [6]. According to this, linear dependence of polymer solution viscosity on polymer and salt concentration can be written as [10]:

$$\mu_w = \mu_{w0}\left(1 \pm \gamma_p \mathrm{c}_1 + \gamma_s c_s\right) \quad (6)$$

where γ_p, γ_s – constants, μ_{w0} – initial viscosity of solution. Sign «+» at gellan injection, « - » at PAAm injection.

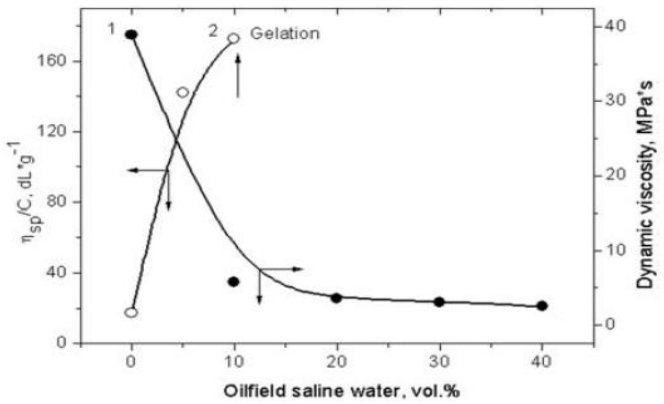


Figure 1: Dependence of the dynamic viscosity of PAAm (1) and gellan (2) solution on salinity of oil field water.

The relation between the concentration of adsorbed polymer and polymer concentration in solution is linear and described by Henry isotherm [8]:

$a = \Gamma c_p$

Obviously, adsorption of polymer leads to a reduction of permeability, which leads to a decrease in mobility. The coefficient of permeability reduction R_k can be defined as follows (R_{RF}- residual reduction factor) [11]:

$$R_k = 1 + (R_{RF} - 1)a \tag{7}$$

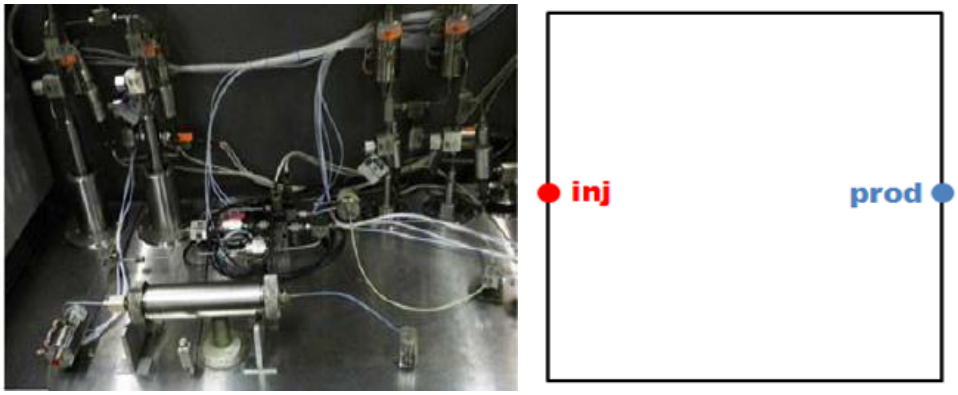
Relative permeability curves are taken as follows:

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

3 Numerical Results and Model Verification

To validate proposed model two stages of verification are conducted: comparison of results with laboratory experiments and with results of calculations on hydrodynamic simulator Eclipse 100.

First stage. Verification of abovementioned model is based on the results of the laboratory experiment conducted by research group of "Engineering specialization Laboratory", leaded by Kudaibergenov S. E. Investigation of oil displacement in cores with water and polymer solution performed on UIC - C (2) [5, 6] installation, which is shown in Figure 2a. Input data for numerical simulation of this process (which is fully consistent with experimental data) are shown in Table 1.



a) b)

Figure 2: a) Core holder UIC - C (2); б) Well locations (numerical simulation)

Parameter	Value	Parameter	Value
Porosity, m	0,37	Oil Viscosity, μ_{oil}	8,09 mPa·s
Permeability, k	0.322 Darcy	Water Viscosity, μ_{wat}	0,9 mPa·s
RRF, R_{RF}	1,2	Adsorption Constant, Γ	0,1m^3/kg
Concentration of injection Gellan Solution, C_{inj}	0,1%	Initial Salt Concentration (NaCl), C_{init_salt}	73 g/l

Table 1**:** Physical parameters used in simulation

For comparison of numerical model results with experimental results conducted on UIC – C (2) we rewrite the system of equations (1) - (5) in cylindrical coordinates.

Mass conservation laws:

$$m\frac{\partial S_w}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(rK1_r\frac{\partial P}{\partial r}\right) + \frac{1}{r^2}\frac{\partial}{\partial \varphi}\left(K1_\varphi\frac{\partial P}{\partial \varphi}\right) + \frac{\partial}{\partial z}\left(K1_z\frac{\partial P}{\partial z}\right) \quad (8)$$

$$m\frac{\partial S_o}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(rK2_r\frac{\partial P}{\partial r}\right) + \frac{1}{r^2}\frac{\partial}{\partial \varphi}\left(K2_\varphi\frac{\partial P}{\partial \varphi}\right) + \frac{\partial}{\partial z}\left(K3_z\frac{\partial P}{\partial z}\right) \quad (9)$$

Polymer concentration:

$$m\frac{\partial}{\partial t}(c_1 s) + \frac{\partial a}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}(r(c_1\vec{v}_1)_r) + \frac{1}{r}\frac{\partial}{\partial \varphi}\left((c_1\vec{v}_1)_\varphi\right) + \frac{\partial}{\partial z}((c_1\vec{v}_1)_z) = \frac{1}{r}\frac{\partial}{\partial r}\left(rD_r\frac{\partial c_1}{\partial r}\right) + \frac{1}{r^2}\frac{\partial}{\partial \varphi}\left(D_\varphi\frac{\partial c_1}{\partial \varphi}\right) + \frac{\partial}{\partial z}\left(D_z\frac{\partial c_1}{\partial z}\right) \quad (10)$$

Salt concentration:

$$m\frac{\partial}{\partial t}(c_s s) + \frac{1}{r}\frac{\partial}{\partial r}(r(c_s\vec{v}_1)_r) + \frac{1}{r}\frac{\partial}{\partial \varphi}\left((c_s\vec{v}_1)_\varphi\right) + \frac{\partial}{\partial z}((c_s\vec{v}_1)_z) = 0 \quad (11)$$

By adding (8) and (9) we obtain pressure equation:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(rM_r\frac{\partial P}{\partial r}\right)+\frac{1}{r^2}\frac{\partial}{\partial \varphi}\left(M_\varphi\frac{\partial P}{\partial \varphi}\right)+\frac{\partial}{\partial z}\left(M_z\frac{\partial P}{\partial z}\right)=0 \tag{12}$$

$$M(r,\varphi,z)=K1(r,\varphi,z)+K2(r,\varphi,z);$$

$$K1(r,\varphi,z)=\left.K_0\frac{f_w}{\mu_w}\right/_{R_k};\qquad K2(r,\varphi,z)=K_0\frac{f_o}{\mu_o}$$

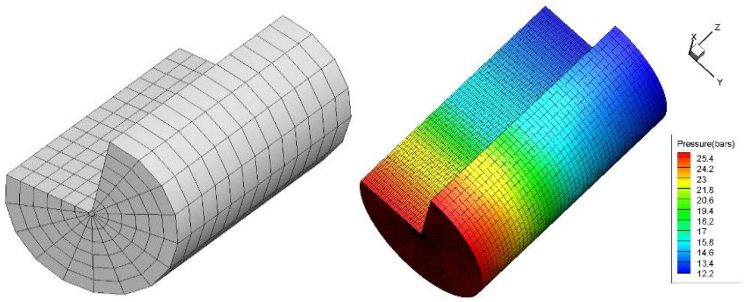
Initial and boundary conditions:

$$s|_{t=0}=S_0,\ \ c_p\big|_{t=0}=C_{0p},\ \ c_s|_{t=0}=C_{0s}, \tag{13}$$

$$\begin{aligned}
&s|_{z=0}=S_{inj}, && \left.\frac{\partial s}{\partial z}\right|_{z=L}=0; && \left.\frac{\partial s}{\partial r}\right|_{\partial\Omega}=0; && \left.\frac{\partial s}{\partial \varphi}\right|_{\partial\Omega}=0;\\
&c_p\big|_{z=0}=C_{inj}, && -D\left.\frac{\partial c_p}{\partial z}\right|_{z=L}=0; && \left.\frac{\partial c_p}{\partial r}\right|_{\partial\Omega}=0; && \left.\frac{\partial c_p}{\partial \varphi}\right|_{\partial\Omega}=0;\\
&c_s|_{z=0}=C_{s_inj}, && \left.\frac{\partial c_s}{\partial z}\right|_{z=L}=0; && \left.\frac{\partial c_s}{\partial r}\right|_{\partial\Omega}=0; && \left.\frac{\partial c_s}{\partial \varphi}\right|_{\partial\Omega}=0;
\end{aligned} \tag{14}$$

In order to obtain consistency of units and order of variables, the system of equations (8) - (14) are converted to dimensionless form. All equations are solved in explicit scheme [12]. Firstly, the initial value of oil saturation, technological parameters of reservoir and physical parameters of fluids in both phases are set. Further, calculations are carried out according to following order:

- pressure distribution is calculated;
- saturation (by known distribution of pressure) is calculated;
- distribution of salt and polymer concentrations is calculated;
- viscosity of aqueous phase is recalculated;
- aqueous phase permeability is recalculated.



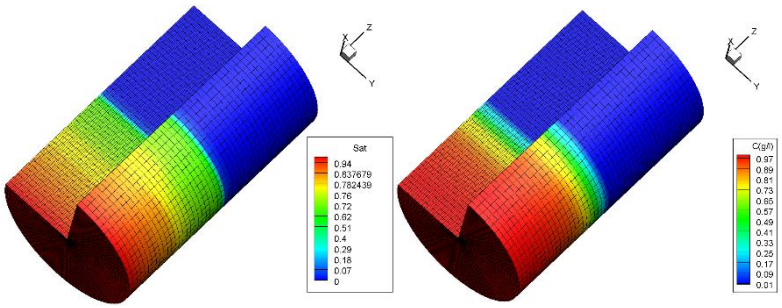
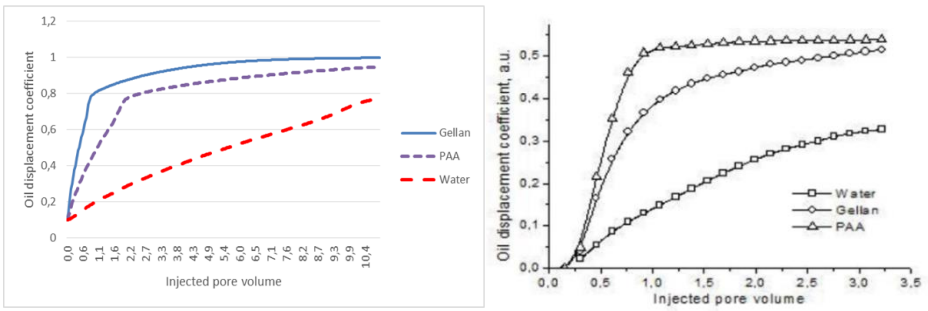


Figure 3: Distribution of pressure, water saturation and polymer concentration in the core



a) b)

Figure 4: Dependence of recovery rate on injected pore volume of fluid
a) numerical b) experimental study

Numerical results are shown in Figure 3. Figure 4 shows dependence of oil displacement on injected pore volume obtained by numerical and laboratory studies. It can be noted that oil displacement by polymer shows much higher recovery ratio compared to water displacement. Oil displacement efficiency of gellan and polyacrylamide at about same level, which is confirming results of the experimental study.

Second stage. To compare numerical results with Eclipse 100 simulator two dimensional problem is considered. Parameters of reservoir and properties of porous media and fluids (water, oil) for numerical calculation is absolutely identical to values used in the calculation on the Eclipse simulator.

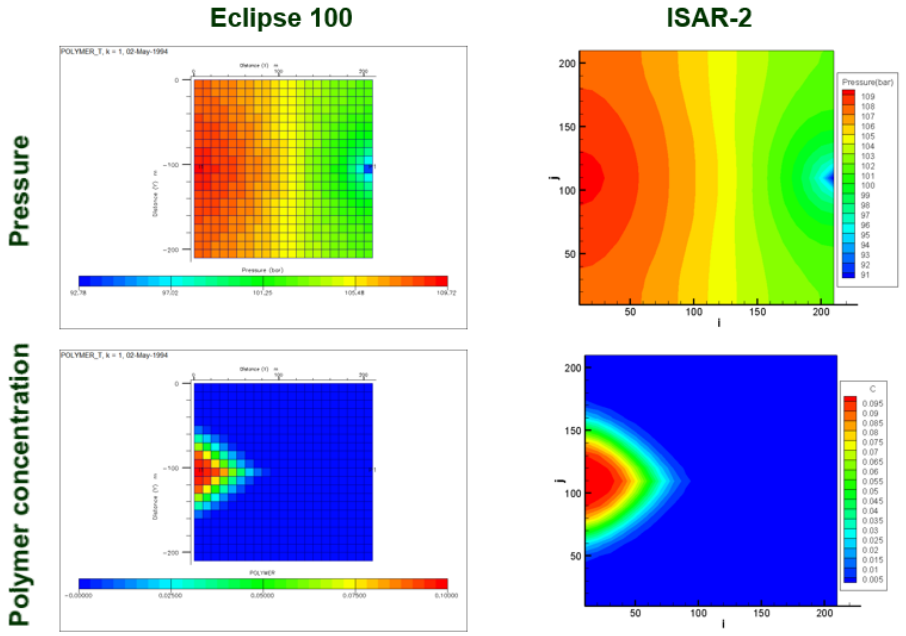


Figure 5: Distribution of pressure and polymer concentration

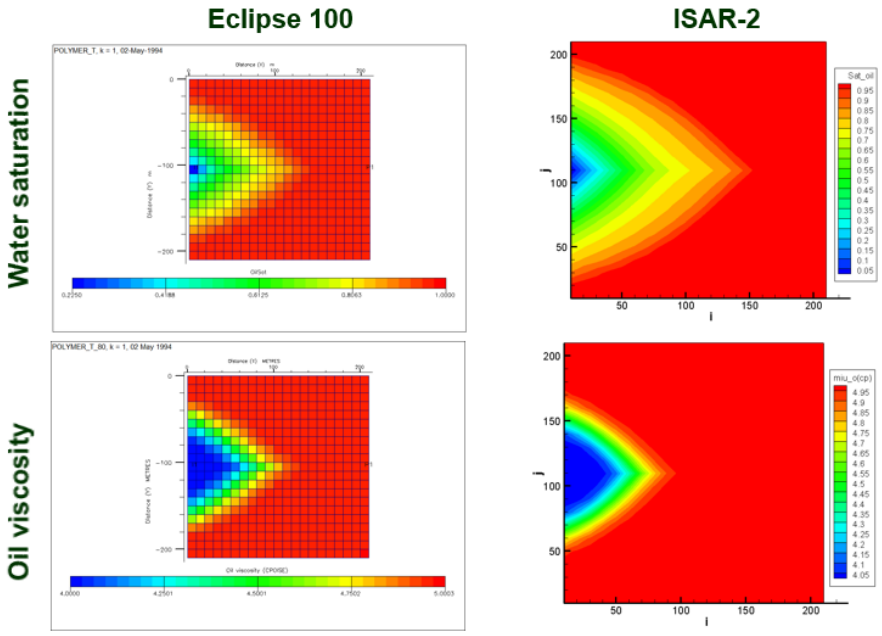


Figure 6: Distribution of water saturation and oil viscosity

Results of numerical calculations of distributions pressure, saturation, and polymer concentration are presented in two-dimensional area (Figure 5) as well as in the straight line connecting the injection and production wells (Figure 6). The 210m x 210m oil reservoir is taken as computational domain. On injection and production wells corresponding pressures equal to 110 atm. and 90 atm. are set. Reservoir pressure is taken as 100 atm.

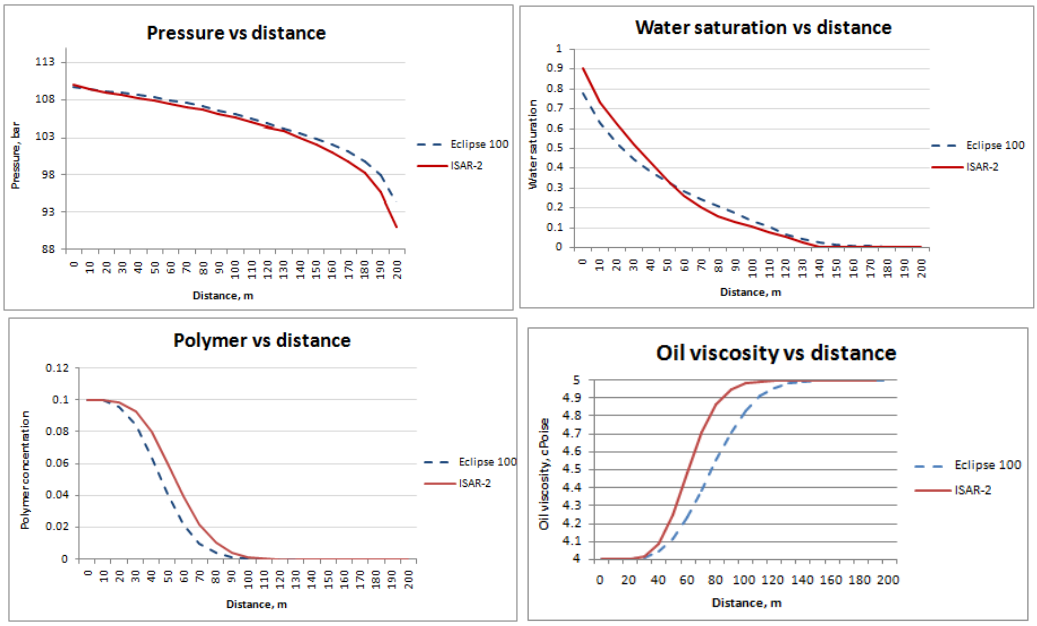


Figure 7: Distribution of main parameters in the line connecting two wells

In Figure 7 it can be seen that after 120 days of polymer solution injection, the distribution of pressure, water saturation and concentration of the polymer is more or less match with results of the Eclipse simulator. However, a significant difference in distribution of oil viscosity is related to the difference of the used dependence of viscosity from salt and polymer concentration used in Eclipse [13] and ISAR-2 simulators.

4 Distributed Computing System for the Analysis of oil Fields

There are many approaches to development of the software tools for analysis and development of oil and gas fields. For example, smart fields, i-fields, e-fields concept of information system proposed by specialists of Stanford University (USA) aimed to optimize operations in oil and gas field in continuous mode, plan location and number of new wells. When considering large and complex oil and gas

fields implementation of such technologies requires their qualitative research. Operational decision-making and optimal exploitation of fields suggests need for modeling and control of data fields in real-time using modern software and hardware. Above statements can be combined in model of the "closed-loop intelligent field", shown in Figure 8, there are two main components of cycle can be seen: modeling and prediction of processes in oil and gas reservoirs [14].

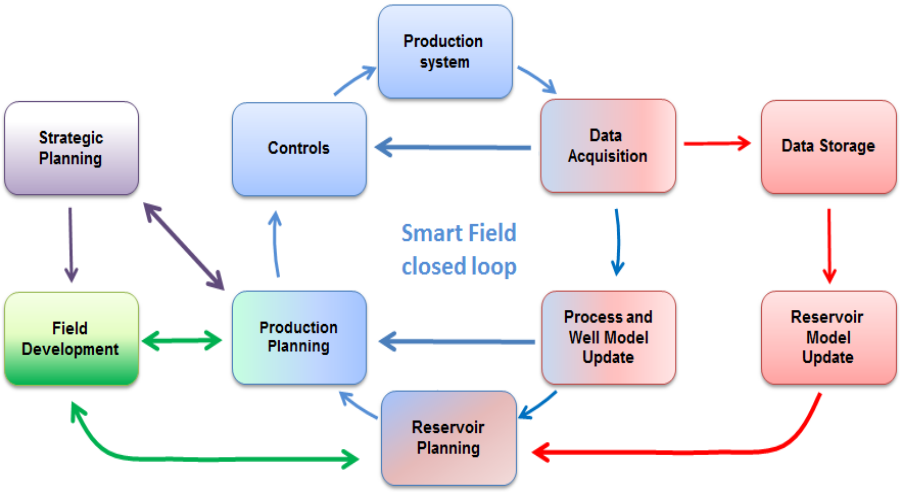


Figure 8: A "Closed-loop intelligent field" scheme (Smart Fields Consortium, Stanford University, USA)

Uniqueness of proposed system is in development of architecture, components and interfaces of distributed computing system and software modules for calculation of technical and production indicators of oil production technological problems considering specific conditions of the field. All calculations are carried out with computing resources located in one city, the primary database is in another. User, in his turn, performs calculation and analysis of results related to selected model of technological problem in oil field conditions via engineer's automated workplace connected to Internet. Input and output of data can be simultaneously carried out from anywhere in the country if there is access to the Internet. Thus, the system can be complemented by new models of technological tasks and quickly updatable. The approximate scheme, model infrastructure and architecture of the distributed computing system presented in Figure 9.

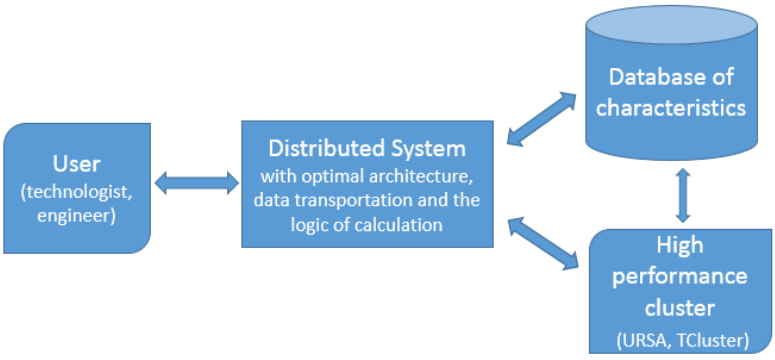


Figure 9: Architecture of distributed information system

Proposed system has following advantages: free access from anywhere in the country via the Internet (including mobile platforms); analyzer software can be placed on any high-performance resource that facilitates the process of administration, service, debugging, and refinement of the program; all complex calculations will be performed on multiprocessor computing clusters, which significantly reduces decision making time; ability to connect, integrate and select real-world data from a databases of head offices of oil companies or production fields.

5 3D Web Hydrodynamic Simulator

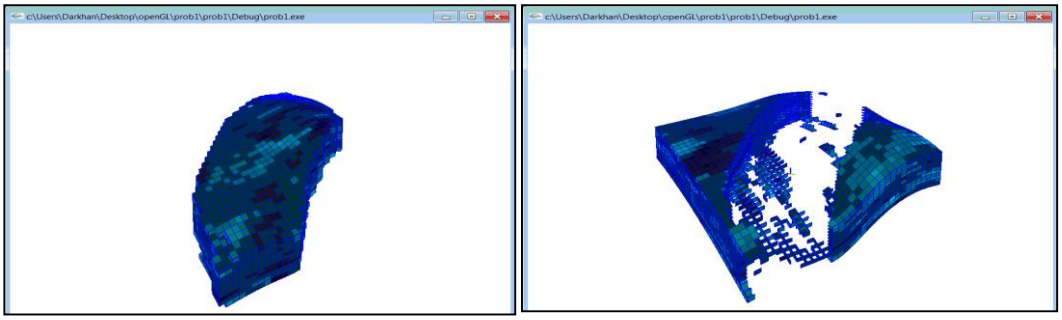
The system represents interactive package for analysis and estimation of technological problems of hydrodynamic simulation of oil and gas fields. The basis of the produced program complex the modern scientific developments which allow to use heterogeneous multiprocessing computer facilities at their 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 [15].

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. 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 10).

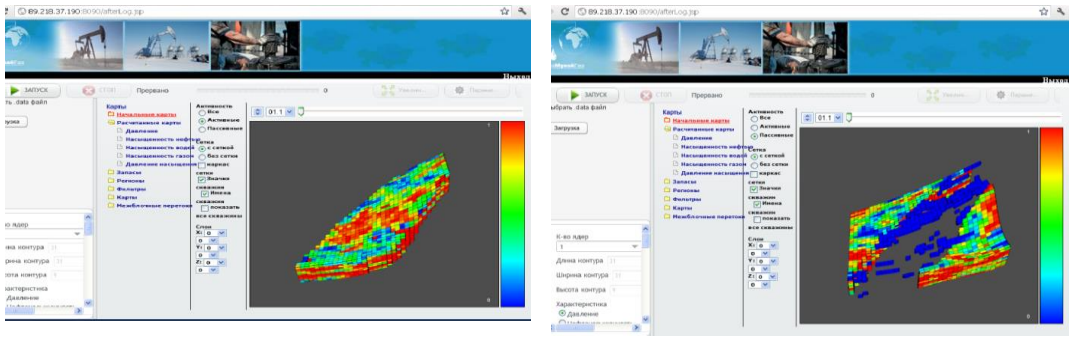
2) As a Web-module running on the server (supercomputer) and partially using hardware of graphics subsystem of client computer. Visualization is carried

out on the basis of WebGL graphical technology, with JavaScript, HTML5 web-technologies (Figure 11).



a) b)

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



a) b)

Figure 11: 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.

6 Calculations on the Combined Metacomputer

Figure 12 shows the computation time of parallel program which solves the above problem by Jacobi method. Calculations were performed on clusters of Mechanics and Mathematics Faculty of al-Farabi Kazakh National University called Ursa and TCluster [16] and on their combination for different number of processors.

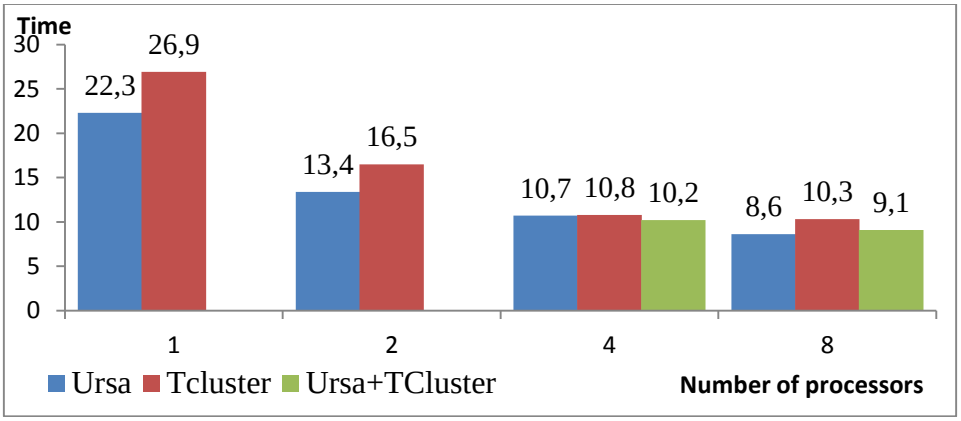


Figure 12: Execution time of program for above problem on 200x200 grid

Obtained values of speedup and efficiency are significantly depend on current load of the cluster with tasks. Therefore, they can vary during the day when calculation were held. One of solutions to this problem is to run tasks when cluster resources are idle. However, this is not always achievable. Another approach to solve this problem is to distribute the load between two or more clusters, organizing a metacomputer consisting of multiple clusters connected to each other. In order to combine clusters special software NumGrid [17] were used. Purpose of its use when solving this problem was to increase the amount of computing resources by combining two clusters, which will increase the scale of the problem being solved. Figure 12 shows when using two clusters computation time is comparable with the time based on the single cluster, which is an acceptable result, considering the purpose of the NumGrid software.

7 Conclusion

1) A mathematical model of oil displacement process by polymer injection, which takes into account salinity of the reservoir water, dependence of polymer solution viscosity on polymer and salt concentration and effect of the polymer adsorption on permeability of the aqueous phase is considered.

2) The equation system is solved by an explicit iterative method and following numerical results are obtained: the distribution of pressure, saturation of both phases, the polymer and salt concentrations and oil displacement efficiency.

3) The efficiency of oil displacement of water and polymer flooding was compared. It has been shown that oil displacement rate with polymer flooding is much higher than water flooding.

4) Verification of the model is conducted by comparing the numerical results with experimental studies.

5) The module of polymer injection analysis of distributed information system for analysis (ISAR-2) of oil the field development with operational monitoring in real time and possibility of computing via remote access or Internet oil.kaznu.kz portal is developed.

6) 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).

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