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SELECTION OF PROXY MODELLING METHODS FOR STREAMLINE SIMULATION TO WATERFLOODING MANAGEMENT PROCESS IN OIL RESERVOIRS

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ABSTRACT

Proxy modelling which uses a number of predetermined reliable parameters due to its simplicity has been widely used for the analysis of gas and oil field development in comparison to the traditional mathematical three-dimensional (3D) hydrodynamic models. Among the reservoir models with simplified physics the streamline simulation is favorably characterized by its visibility and informativeness. In this work MATLAB as well as COMSOL Multiphysics modules were used for streamline simulation of flow in porous media using known volumes of injected and produced fluid in a reservoir with known permeability and porosity for sequential waterflood treatment. The comparative analysis showed that after one month of the treatment the front of the injected water advancement became smoother. Comparing the dynamics of the location of the lines characterizing the filtration state of the area before and after the impact on the reservoir, it was found that the productivity of production wells depends not only on how close they are located to the injection well, but also on the activity of the filtration zone. Based on an analysis of the preferred directions of fluid movement after sequential waterflooding, it was determined that oil in some previously unaffected areas was also displaced by the injected fluid. The results obtained by MATLAB and COMSOL Multiphysics modules were analyzed comparatively.

Keywords: proxy modelling; streamline simulation; COMSOL Multiphysics; MATLAB; Darcy's law; reservoir models.

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1. Introduction

Many oil fields in the world are at a late stage of development, which utilize secondary and tertiary treatments to enhance oil recovery, among which waterflood systems are the mainstay [1-3]. At each of them, in order to increase oil production, measures are taken to improve the system of impact on productive formations by injecting water and other working agents [4]. Various types of analysis of the reservoir system state under the influence of geological and technical measures, taking into account the history of development and field exploration, are used to select optimal methods of impact on productive strata [5, 6]. Simulation modelling based on the use of the laws of underground hydrodynamics has become widespread [7-10]. When designing reservoir stimulation using this approach, the calculation procedure develops into a long-term process requiring updating of numerous initial data and model adaptation to real field conditions. Continuous permanent design does not allow to adequately assess the current hydrodynamic state of the productive formation and the nature of its changes under the influence of methods of impact, carried out both zonally and in the whole formation [11].

It requires the development of mathematical models, express methods and algorithms, implementation of software products, which allow the rapid solution of problems of diagnostics of the filtration condition of the reservoir system. These models should indicate the way to the design of methods of impact on oil and gas fields in accordance with the current distribution of formation fluids in the productive formation, as well as allow to assess the actual efficiency of the applied methods [16-18]. Many methods exist for building three-dimensional reservoir models.

The theoretical basis and results of using a fast three-dimensional super-element model of oil field development are described in the papers [19, 20]. The model, by using large computational cells – super-elements, the number of which corresponds to the number of wells in the field, makes it possible to accelerate the calculation of two-phase filtration in an oil reservoir hundreds of times.

The Capacitance Resistivity Model (CRM) has been developed for fields with minimal reservoir data or for small fields that do not require a full reservoir simulation model, which can be time consuming and costly [18, 21].

The streamline method is three dimensional (3D) designed to model flow in porous media and accounts for changing well conditions that result from infill drilling and well conversions, heterogeneity, mobility effects, and grav-

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ity effects [22-26]. Streamlines represent a snapshot of the instantaneous flow field and flow rate allocation between injector/producer pairs that are not easily determined by other simulation techniques [27]. In [23] the theory of the streamline method is described and the predictions using the streamline technique against two-dimensional numerical simulations of incompressible miscible flow are compared. The streamline method is more than 100 times faster than conventional simulation.

In this context, various approaches for fast and reliable prediction of flow dynamics under different optimization scenarios are required for operational control and optimization of the waterflood system. In this paper, we used MATLAB as well as COMSOL Multiphysics modules for streamline simulation of flow in porous media using known volumes of injected and produced fluid in a reservoir with known permeability and porosity for sequential waterflood treatment of this reservoir. The results obtained by these two approaches were analyzed comparatively.

2. Methods

2.1 Express monitoring using MATLAB

The proposed method of diagnostics is based on the use of elements of the theory of complex potential functions. The subject of diagnostics can be both the productive reservoir of the field as a whole, which is a complex, highly organized dynamic system, and its individual components - zones of the productive horizon within a block, group of wells or drainage zones of individual wells.

The basic principles of hydrodynamic express-monitoring used to analyze the hydrodynamic state of the reservoir system in the studied area of the productive horizon by applying the methods of the theory of complex potential functions, taking into account the interference of wells, are described in [28-30].

The following summarizes the algorithm that allows to calculate for each grid cell in the investigated field zone the values of the current and potential functions F_1 and F_2, the characteristic flow function or complex potential F, the filtration rate modulus W, and the gradient of the function $F(x,y)$. Injection wells are taken as sources (flow rate <0), and production wells as sinks (flow rate >0). The problem is solved in Cartesian (x_k, y_k) and polar coordinates (r, φ):

$$z_k=x_k+i\cdot y_k=r_\kappa\cdot e^{i\cdot\phi k} \tag{1}$$

The expression for the complex potential has the form:

$$F=F_1+i\cdot F_2 \tag{2}$$

According to the principle of superposition to simultaneously operating in the reservoir drains and sources:

$$F_1=\sum_{i}^{n}\sum_{k=1}^{K}\sum_{j=1}^{J}\frac{q_i}{2-\pi}\ln(r_i(k,j)),\quad F_2=\sum_{i}^{n}\sum_{k=1}^{K}\sum_{j=1}^{J}\frac{q_i}{2-\pi}\varphi_{i,j} \tag{3}$$

Filtration rate modulus:

$$W=\left|\frac{dF}{dz}\right|=\sum_{i}^{n}\sum_{k=1}^{K}\sum_{j=1}^{J}\frac{q_i}{\pi r_i(k,j)} \tag{4}$$

Function gradient $F(x, y)$:

$$grad(F)=(dF(x,y)/dx)\cdot i_v+(dF(x,y)/dy)\cdot j_v \tag{5}$$

where: z_k and x_k, y_k – respectively, complex and real coordinates of a well; g_k, φ_k – respectively, the distance from the well to the origin of coordinates and polar angle; k=1, ...n – the number of wells in the considered area, q_k, F_1, F_2 – respectively, the flow rate of a well, filtration rate potential and fluid flow rate per unit cross-section of the formation (i.e., per 1 m of filter);

The above hydrodynamic characteristics are determined in accordance with the principle of superposition to simultaneously operating in the reservoir drains and sources and at time t will be defined as matrices of the form:

$$F_1^t=\begin{bmatrix}(F_1^t)_{1,1} & \dots & (F_1^t)_{1,n}\\ \dots. & \dots & \dots\\ (F_1^t)_{m,1} & \dots & (F_1^t)_{m,n}\end{bmatrix};\; F_2^t=\begin{bmatrix}(F_2^{\,t})_{1,1} & \dots & (F_2^{\,t})_{1,n}\\ \dots. & \dots & \dots\\ (F_2^{\,t})_{m,1} & \dots & (F_2^{\,t})_{m,n}\end{bmatrix};$$

$$W^t=\begin{bmatrix}(W^t)_{1,1} & \dots & (W^t)_{1,n}\\ \dots. & \dots & \dots\\ (W^t)_{m,1} & \dots & (W^t)_{m,n}\end{bmatrix};$$

$$grad(F^t)=\begin{bmatrix}(grad(F^t))_{1,1} & \dots & (grad(F^t))_{1,n}\\ \dots. & \dots & \dots\\ (grad(F^t))_{m,1} & \dots & (grad(F^t))_{m,n}\end{bmatrix} \tag{6}$$

The calculation using the above formulas for each cell of the investigated area with a large number of wells represents a certain complexity. This is the reason why the described methods are not very popular with their high accuracy of the result and practicality of application. On the basis of the presented formulas an original algorithm was developed, which combines in one whole the determination of hydrodynamic parameters of formation fluids in the considered area. In order to obtain accurate results, the procedure of automation of calculation and visualization of values of current, potential, filtration velocity functions and their gradients in the area with an arbitrary number of interacting wells is used. For realization of this procedure the system of engineering and scientific calculations MATLAB is used [31].

As a result of calculations on MATLAB, maps of the filtration field characteristics are obtained, which determine the current localization, velocity and direction of filtration flow propagation along the strike of the investigated area. Standard data for each well operating at the site are used for the calculations: current flow rate of producing wells by liquids (oil and water), tons/day; current injection volume into injection wells, m^3/day; conditional coordinates of well location, m; well filter thickness, m; the densities of produced oil, water and injected liquid kg/m^3; are specified accordingly. The data on well flow rates and injection volumes should correspond to each other according to the date of measurement.

For each grid cell of the study area partitioning, numerical calculation of the total values of the functions F_1^t, F_2^t, F^t and W^t is performed sequentially. Then, maps of distribution of current lines, equipotential, filtration rate and their gradients are plotted.

The reliability of the developed methodology is confirmed by the data obtained in laboratory-experimental studies of oil displacement on a physical reservoir model and in field conditions with tracer studies [32].

The presented methodology has been successfully tested several times for operative estimation of the current state of the productive formation at zonal impact on the formation in order to increase oil recovery at such onshore and offshore fields of Azerbaijan as Balakhany-Sabunchu-Romani, Pirralahi, Oil Stones, Gunashli [32].

2.2. Proxy modeling based on COMSOL Multiphysics

Reservoir models with simplified physics are required to quickly and reliably predict the flow dynamics for different optimization scenarios for the operational control and optimization of a waterflood system. Recently, proxy modelling has been increasingly used for the analysis of gas and oil field development in comparison to the traditional mathematical 3D hydrodynamic models [11-17, 33]. It is a simplified method which uses a number of predetermined reliable parameters. These include super-element models [19, 20], CRM (Capacity-Resistance Model) [21, 34], streamlines [22, 35] and displacement characteristics [36] etc.

To model the pressure distribution pattern in the near-surface zone of a reservoir during waterflooding, we can apply software modules developed in the COMSOL Multiphysics software environment using known volumes of injected and produced fluid in a reservoir with known permeability and porosity before and after treatment of this reservoir. This approach is simple and quickly leads to results that are in satisfactory agreement with experimental results. Based on the results obtained, the future performance fate of the wells under study can be easily predicted. Below are the basic principles of mathematical modeling used in COMSOL Multiphysics.

Hydrodynamics of fluid flow in Darcian porous media when oil is displaced by water in a set of wells is modeled using Darcy's law (dl). Darcy's law is a simulation of the fluid flow through a porous medium, where the pressure gradient is the dominant force. This is useful for modelling laminar flows through a porous media where the permeabilities and porosities are very small, and flow is mainly influenced by pore friction. The main feature is the Fluid and Matrix Properties node. This provides an interface for defining the fluid material together with the porous medium properties. For the simulation, a rectangular region of length *L* and width *W* was selected, within which two injection wells and 14 production wells were located (table 1). In this model we used as the displacing fluid water of viscosity μ_1 and density ρ_1, and as production fluid oil of viscosity μ_2 and density ρ_2. The governing equations are the equation of continuity - conservation of mass, and the equation of motion for fluid velocity - conservation of momentum.

The velocity field is determined by the pressure gradient (∇p), the viscosity of the fluid (μ) and the structure of the porous medium via permeability (K), according to Darcy's law [37, 38]:

$$\nabla \cdot \boldsymbol{u} = 0 \tag{7}$$

$$\boldsymbol{u} = -\frac{K}{\mu} \nabla p \tag{8}$$

where $\boldsymbol{u} = (u, v)$ and μ are the Darcy-velocity.

The Darcy's Law interface combines Darcy's law with the continuity equation,

$$\frac{\partial \rho \varepsilon_p}{\partial t} + \nabla \cdot \left(\rho \boldsymbol{u} \right) = Q_m \tag{9}$$

where ρ is the fluid density, ε_p is the porosity, and Q_m is a mass source. Porosity is defined as the fraction of the control volume that is occupied by pores. Thus, the porosity can vary from zero for pure solid regions to unity for domains of free flow.

3. Result discussion

Analysis of the current state of the reservoir system is carried out on the example of the data obtained during the assessment of sequential waterflooding on the productive layer of Gunashli field for the period 01.08.2023-01.09.2023. 16 wells, including 2 injection wells, were operated in the study area during the period. Based on the information about the productivity of the production and injection wells operating in the period under consideration for the study area (table 1), the maps of pressure distribution in injection and production wells and streamlines for reservoir fluid, obtained by MATLAB and COMSOL Multiphysics modules (fig. 1 and 2) were constructed.

As an example of using the Express monitoring on MATLAB we present the results obtained when assessing the sequential waterflooding impact on the reservoir of the Gunashli field. Figure 1 shows maps of the distribution of various hydrodynamic characteristics at 01.08.2023 (a) and the same characteristics a month later (b). Changes in the localization, density and color of the lines allow decisions to be made about the results of the impact and the feasibility of its continuation.

Based on the analysis of the distributions obtained, it was found that the productivity of production wells depends not only on how close they are to the injection well, but also on the activity of the filtration zone in which they operate. It may happen that the well is located in a zone with relatively low activity, but high values and a favorable direction of the gradient of a particular filtration characteristic allow predict-

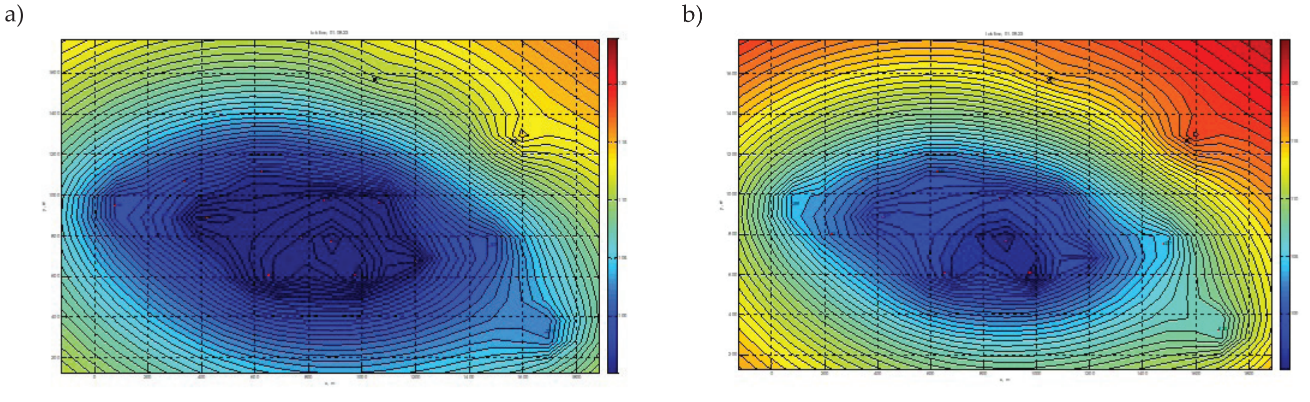

Fig. 1. Distribution of streamlines at the Gunashli field obtained from the MATHLAB modelling: a) at 01.08.2023; b) – a month later

Table 1

Mass flow rate for injection and production wells

Well number	**Mass flow rate (M_0), kg/s**		**Well type**
	01.08.2023	**01.09.2023**	
85	76.33	76.33	Injection
89	131.435	131.435	-“-
160	27.49	27.74	Production
186	52.62	51.04	-“-
188	18.2	19.01	-“-
190	25.56	26.46	-“-
220	10.81	11.85	-“-
330	14.51	11.22	-“-
331	16.05	18.5	-“-
332	10.86	9.43	-“-
333	23.07	21.17	-“-
334	4.25	0	-“-
335	12.4	10.83	-“-
336	19.84	18.22	-“-
337	13.53	13.13	-“-
340	22.1	23.63	-“-

Table 2

Lists of parameters

Length of domain (L), m	1650
Width of domain (W), m	1300
Well diameter (d_w), m	0.1
Line mass source (N_0), kg/(m.s)	35
Inward mass flux (N_0), kg/(m^2·s)	0.04
Porosity of porous matrix (ε)	0.05
Permeability of porous matrix (k), m^2	$0.54 \cdot 10^{-5}$
Injection fluid’s dynamic viscosity (μ_1), Pa·s	0.001
Injection fluid’s density (ρ_1), kg/m^3	1000
Production fluid’s dynamic viscosity (μ_2), Pa·s	0.01
Production fluid’s density (ρ_2), kg/m^3	800

ing an increase in well production rate. On the other hand, high activity of the filtration process, directly in the zone of influence of the producing well, together with a high value of the gradient and the direction of flow to the well location, serves as an unfavorable factor, as all this contributes to the process of active transfer of mechanical impurities to the bottom of the well, the creation of sand plugs and damage to the perforation zone of the well. In such cases, it is necessary to consider the optimal well operation mode before stimulating the reservoir.

Considering the dynamics of the current function F_1 and its gradient at the beginning of flooding, it was revealed that water injection carried out at the site has a heterogeneous character. The main mass of water goes to the zone of the field where relatively few wells are located (red lines), which contributes to watering of their production. The main mass of wells is located in the inactive zone (blue lines). If we assume that the optimal impact on the wells is characteristic of the zones with green and yellow lines, we can conclude that the conducted water injection does not meet expectations. The dynamics of equipotential lines shows that at the beginning of flooding the localization zone of most wells has a relatively high potential (the color spectrum of the lines changes from yellow to red). In order to realize this potential, it is necessary to apply methods of impact on the reservoir, equalizing the front of the injected water advancement. Analysis of the map of filtration velocity distribution in the formation showed low values of fluid advance velocity (fig. 1a), which means that a long period of time is required for effective stimulation of the formation. One month after the impact, a second rapid monitoring was carried out (fig. 1b). The comparative analysis showed that after one month the front of the injected water advancement became smoother, but the hydrodynamic activity of the site decreased.

The parameters used in the COMSOL Multiphysics simulations are shown in table 1 and table 2.

Extremely fine free triangular mesh of fluid dynamics is used for discretization of the domain. This meshing provides perturbation of triangular type at the interface.

The streamlines and pressure distribution in the reservoir section where the injection and production wells are located obtained from the COMSOL Multiphysics modelling at the Gunashli field at 01.08.2023 (a) and one month later (b) are shown in figure 2. As can be seen, the pressure in the pro-

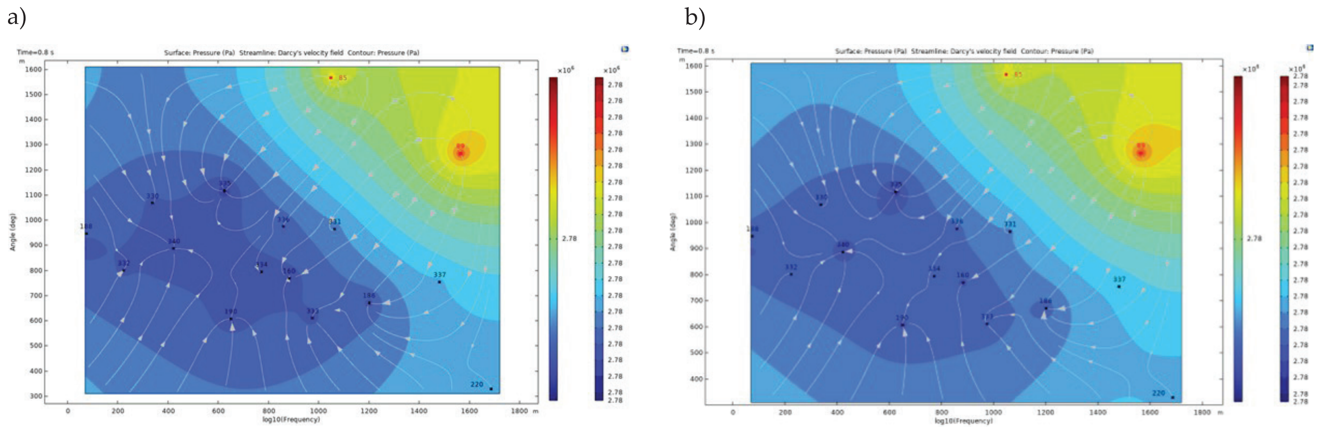

Fig. 2. Distribution of streamlines at the Gunashli field obtained from the COMSOL Multiphysics modelling: a) at 01.08.2023; b) – a month later

duction wells depends strongly on the distance between the injection and production wells, as well as on the permeability of the reservoir. The figure also shows that longer waterflood treatment leads to a flattening of the displacement front. The decrease in the pressure difference between the injection and production wells at the same injection rate shows that the permeability of the corresponding wells increased one month after waterflooding according to Darsy's law. The preferred directions of fluid flow also change after longer waterflood treatments. This means that after longer treatment, oil in some previously unaffected areas is also displaced by the injected fluid.

The proposed methods of calculation and visualization of various indicators characterizing the hydrodynamic state of the reservoir system can be used both independently and in combination, complementing each other. Note that compared to MATLAB, modeling in COMSOL Multiphysics is simple and quickly produces results that are in satisfactory agreement with experimental results. The results can be used to predict the future performance of the well.

Conclusions

1. MATLAB and COMSOL Multiphysics modules were used to predict reservoir flow dynamics during sequential waterflood treatment. The use of the proposed approaches provides certain advantages for rapid analysis of fluid distribution in the reservoir at the impact area. There is no need for in-depth analysis of reservoir properties of rocks and simulation geological and hydrodynamic modeling. Maps of filtration field characteristics were obtained, which determine the current localization, velocity and direction of filtration flows along the strike of the investigated area.
2. Comparing the kinetics of the location of lines characterizing the state of filtration during waterflooding, it was concluded that the productivity of production wells depends not only on how close they are located to the injection well, but also on the activity of the filtration zone in which they operate.
3. The dynamics of equipotential lines in the pilot area of Gunashli field shows that at the beginning of flooding the localization zone of most wells has a relatively high potential. In order to realize this potential, it is necessary to use methods of stimulation of the reservoir to equalize the front of the injected water advance. Analysis of the map of filtration velocity distribution in the reservoir also showed low values of fluid velocity, which means that a long period of time is required for effective stimulation of the reservoir. One month after flooding, repeated rapid monitoring showed that the injection water advancement front became smoother.
4. The COMSOL Multiphysics simulations also show that longer waterflood treatments result in a flattening of the displacement front. The permeability of most wells increases after a long stimulation at constant injection rates.
5. The change in preferred directions of fluid flow after longer waterflood treatments shows that oil in some previously unaffected zones is also displaced by the injected fluid.
6. Modeling in COMSOL Multiphysics compared to MATLAB is simple and quickly leads to results that are in satisfactory agreement with experimental results. Based on the results obtained, it is easy to predict the future performance fate of the wells under study.

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