EXPRESS METHOD OF OIL RECOVERY INCREASE ESTIMATION DUE TO DIVERTER TECHNOLOGY APPLICATION DERIVED FROM RESULTS OF HYDRODYNAMIC STUDIES

ЭКСПРЕСС-МЕТОД ОЦЕНКИ УВЕЛИЧЕНИЯ НЕФТЕОТДАЧИ ОТ ПРИМЕНЕНИЯ ПОТОКООТКЛЮЧАЮЩИХ ТЕХНОЛОГИЙ, ПОЛУЧЕННЫЙ НА ОСНОВЕ РЕЗУЛЬТАТОВ ГИДРОДИНАМИЧЕСКОГО МОДЕЛИРОВАНИЯ

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Abstract. There were numerical experiment results within simulation of diverter technology application. They reflect influence of geological uncertainties factors and technological realization of this enhanced oil recovery method.

A set of studies that reproduce as an influence of reservoir structure, physical and chemical fluids properties as one of technological realization parameters of this technology was run. Also the sensitivity analysis of hydraulic system at heterogeneity of permeability (geological uncertainties) and realization parameters of this technology (injected volumes and solution concentrations) was shown.

The making of hydrodynamic model of geological reservoir includes several steps: collection and analysis of input data, initialization and history matching. Each of them takes important part of time that is necessary for mathematical runs in detail. Also the run time of numerical model is from minutes to several hours. On the initial step of decision making about advisability of diverter technology application would be optimally to have an express method allows estimating technological efficiency of operation under the minimal set of input data. And in case of positive decision for runs in detail and for risk estimations it will be suggested to use the tools of hydrodynamic simulation.

Such express method was produced during analysis of numerical experiment results, empirical relationships were derived. They allow estimating a technological efficiency of this technology application. It depends on complex parameter that is
function of heterogeneity of permeability, technological parameters of realization and properties of fluids.

This study will be useful for petroleum engineers. It helps them to make a plan of geological and technical actions, effect forecasts and estimation of technological and economic efficiency. Also this study will be useful for simulation engineers who are on the optimization step of action design.

Аннотация. В работе представлены результаты численных экспериментов по моделированию применения потокоотклоняющих технологий, отражающих влияние факторов геологических неопределенностей и различных технологических реализаций данного метода увеличения нефтеотдачи.

Было проведено множество расчетов, отражающих влияние как строения залежи, физико-химических характеристик насыщающих пласт флюидов, так и технологических параметров реализации МУН. Также представлен анализ чувствительности системы к неоднородности объекта по проницаемости (геологические неопределенности) и параметрам реализации данной технологии (объемы закачек и концентрации растворов).

Создание гидродинамической модели залежи включает в себя несколько этапов: сбор и анализ исходной информации, инициализация и адаптация к истории. Каждый из перечисленных этапов занимает достаточно долгое время, которое необходимо для детальных математических расчетов. Также и само время расчета модели колеблется от минут до нескольких часов. На начальном этапе принятия решения о целесообразности применения данной технологии МУН было бы оптимально иметь какой-либо экспресс-метод, позволяющий при минимальных входных данных определить технологическую эффективность операции. А, в случае положительного решения, для детальных оценок эффекта от мероприятия и рисков предлагается использовать средства гидродинамического моделирования.

Такой экспресс-метод был создан в процессе анализа результатов численного эксперимента, получены эмпирические зависимости, позволяющие оценить технологическую эффективность применения данной технологии в зависимости от комплексного параметра, который является функцией неоднородности проницаемости объекта, технологических параметров реализации технологии и свойств насыщающих пласт флюидов.

Данная работа будет полезна инженерам-нефтяникам при планировании геолого-технических мероприятий, прогнозировании эффекта и расчете технологической и экономической эффективности. Также она будет полезна инженерам в сфере гидродинамического моделирования при выборе оптимального решения на этапе планирования мероприятий.
Keywords: hydrodynamic simulation, mathematical simulation, diverter technologies, polymers, efficiency prediction, express method, numerical experiment, correlations, recovery factor increase.

Ключевые слова: гидродинамическое моделирование, математическое моделирование, потокоотклоняющие технологии, полимеры, прогнозирование эффекта, экспресс-метод, численный эксперимент, корреляции, прирост КИН.

Currently the most of Russian oilfields are on the final development stage. It is characterized by high watercut values and decreases of oil production. Diverter technology application becomes more important than yesterday.

The main problem is estimation of effect before technology realization, not only after it. In other words, we need the prediction, design of diverter technology application [1].

The making of hydrodynamic model of geological reservoir includes several steps: collection and analysis of input data, initialization and history matching. Each of them takes important part of time. Also the run time of numerical model is from minutes to several hours. It depends on complexity and resolution. Runs in detail including all steps of model making and history matching take important part of time that is required for actions planning.

So we need an express method allows estimating of technological efficiency that would be basis of economic viability studies on first approximation.

Starting from the problem to solve it is clear that input data of method must include parameters that influence both incremental oil production and activity costs.

The numerical experiment was run [2] and it resulted in estimation of model sensitivity at the main input parameters [3]. Also analysis was conducted based on that the empirical relationships between oil recovery increase and complex parameter were derived.

The treatment volumes, solution viscosity (that is function of polymer concentration), reservoir heterogeneity have a main impact on efficiency of technology application [4, 5]. So, numerical experiment implies estimation of model sensitivity at entire input dataset. Also it is important to know how much each variable affects action efficiency individually (when residual variables are constants). It is necessary to define a parametric space whose coordinates are parameters selected and the function to be investigated is oil recovery increase (dimensional or dimensionless). At each experiment realization a selected variables (injection volume, concentration, property that characterizes heterogeneity of reservoir permeability) were varied. And by formula 1 the criterion function was being estimated. It is dimensionless variance of oil recovery factor.

$$
\Delta RF = \frac{\sum \Delta Q_o}{STOIIP \cdot RF'},
$$

(1)
where $\sum \Delta Q_o$ – incremental oil production, m$^3$;
$\Delta RF$ – relative variance of oil recovery factor, dim.;
$STOIIP$ – stock tank oil initially in-place, m$^3$;
$RF'$ – oil recovery factor in case of no technology application, dim.

Description of lateral permeability distribution is the variation coefficient:

$$
\nu = \frac{\sigma}{\bar{k}},
$$

(2)

$$
\sigma = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (k_i - \bar{k})^2},
$$

(3)

$$
\bar{k} = \frac{\sum_{i=1}^{n} k_i}{n},
$$

(4)

where $\nu$ – variation coefficient, dim.;
$\sigma$ - mean square deviation, dim.;
$\bar{k}$ - simple average, mD;
$n$ – sample volume, units;
$k_i$ – sample entry, mD.

Based on the hydrodynamic model [1] of layer-heterogeneous reservoir there was created a template that was basis of each variant of studies. Variation limits of parameters were defined by technological and physical restrictions. Workflow algorithm of experiment is shown below:

1. Parameterization of model
2. Creation of the realizations set with completing all selected nodes of parametric space (with variance of one parameter there is no variance of two residual parameters)
3. Variants calculation
4. Estimation of technological efficiency of each realization [1]
5. Sensitivity analysis of hydraulic system at input data

The values of coordinate points are below:

Table 1. Description of parametric space

<table>
<thead>
<tr>
<th>Values of parameters</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concentration, kg/m$^3$</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>10</td>
</tr>
<tr>
<td>Variation coefficient of $k_x$, dim.</td>
<td>0.5</td>
<td>0.8</td>
<td>1</td>
<td>1.2</td>
<td>1.5</td>
<td>2.0</td>
<td>3.0</td>
<td>4.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Injected volume, m$^3$</td>
<td>225</td>
<td>450</td>
<td>600</td>
<td>825</td>
<td>1050</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Realization summary, units</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>400</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
After calculation of whole set of variants and oil recovery increase estimation it was necessary to conduct an analysis of system sensitivity. It was being performed by both visual control of response function behavior and quantitatively. Visual control depends on dimension of parametric space. For example, if the function depends on one variable than its image is 2D plot, if function is dependence of two variables – surface. If dimension is more than 2 – there is no visual image. In this case only different coordinate projections make sense.

Below there is a function projection of relative oil recovery factor (RF) variance on the axes of variables “injection volume” $V_{inj}$ and “concentration” $C$ (when residual third variable - variation coefficient $v$ - is a constant and equals 1.4795).

![Function projection of relative oil recovery factor variance on the axes of variables “injection volume” $V_{inj}$ and “concentration” $C$](image)

Figure 1 shows that with increase of both parameters there is increase of function also. It should be mentioned that response surface in $C$-direction is steeper than in $V_{inj}$-direction. Consequently, with other things being equal, first parameter affect oil recovery factor increase more strongly than second one. This conclusion is useful for action planning and calculation of economic values.

Also it will be useful to investigate different “coordinate-slices” of response function throughout each dimension.

For example, fixing the injected volume of solution and variation coefficient of permeability at values $225$ m$^3$ and 1.4795 respectively, let conduct analysis of relationship between increase RF and concentration that is shown on the figure 2. This
dependence has a high partial correlation coefficient 0.985 and it is characterized as an “extremely close connection” [6]. At the same time, making other slice, changing fixed parameters (injected volume \( V_{\text{inj}} = 225 \) m\(^3\), variation coefficient \( v = 3.0 \)), we can see from the figure 3 that increase of oil RF equals a constant value unless certain value of concentration is reached. Also the partial correlation coefficient 0.88 shows loosing of connection between response function and \( C \) parameter. It is evidence that there is flow redistribution with increase of heterogeneity, fractions of layers with so different flow properties increase and, as a result, efficiency of action reduces. Also, noticing absolute values of \( \Delta RF \), we conclude that technology is less efficient at point with \( V_{\text{inj}} = 225 \) m\(^3\), \( v = 3.0 \).

![Graph](image)

**Figure 2.** Cross-section of \( \Delta RF \) surface by plane that is parallel to “concentration” \( C \) axis at \( V_{\text{inj}} = 225 \) m\(^3\), \( v = 1.4795 \)
Figure 3. Cross-section of $\Delta RF$ surface by plane that is parallel to “concentration” $C$ axis at $V_{\text{inj}} = 225$ m$^3$, $v = 3.0$

Now, let fix two other parameters and let conduct analysis of dependence between response function and third residual parameter. Fixed parameters - concentration $C$ and variation coefficient $v$ – will take values 6 kg/m$^3$ и 1.4795, 6 kg/m$^3$ and 3.0 respectively.

Figure 4. Cross-section of $\Delta RF$ surface by plane that is parallel to “Injected volume” $V_{\text{inj}}$ axis at $C = 6$ kg/m$^3$, $v = 1.4795$
In this case other image appears. Both dependences are characterized as ones with extremely close connection ($r$ possess the values 0.952 and 0.969). At $v = 3.0$ the function increases relatively faster than at $v = 1.4795$. But absolute values of oil RF increase are still characterized by smaller values.

To find out a reason of such system behavior it is necessary to study differences in permeability cubes and flow redistribution after technology application for cases with variation coefficients equal 1.4795 and 3.0 with other things being equal.

The model with variation coefficient $v = 1.4795$ (let name it “model 1”) is characterized by following distribution of flow properties:
Figure 6. Frequency bar chart of permeability distribution with $\nu = 1.4795$

This chart shows that quantity of high-conductive layers is relatively minor and the main part of sample is compiled by low- and middle-permeable layers (in this model). For model with variation coefficient $\nu = 3.0$ ("model 2") the distribution is shown on figure 7 and has different shape:

Figure 7. Frequency bar chart of permeability distribution with $\nu = 3.0$
In spite of that there are layers with high permeability (in this model also), the fractions of layers with so different flow properties increase and flatten out. In this case regardless fact that in this model variation coefficient is higher, sample is more uniform (heterogeneity due to dispersion). As a result, fractions of layers with different flow properties are identical approximately.

To do analysis of flows redistribution after treatment, permeability descending sorting of layers was done and distribution of layer cumulative injection was made. Result shown on the figure 8 illustrates that in model 1 fraction of high-permeable layers (reason of water breakthrough) takes up injection of polymer more than one in model 2. It explains that fact of smaller RF increase in case of more heterogeneous model (model 2).

Consequently, it may be assumed that dependence between oil RF increase and variation coefficient of lateral permeability cube is antagonistic. Let check it by plotting histogram of distribution of partial correlation coefficient for dependence \( \Delta RF - v \). The result shown on figure 9 draws conclusion that probably this relationship is “visible” [6]. But one cannot say that this coefficient explicitly and determines strictly monotonous dependence. To prove it, for example, figure 10 was pictured where we can see \( v \) coordinate-slice. It illustrates that there is no unique monotonous dependence. Consequently, above assumption turn out wrong one.

![Figure 8. Layer distribution of cumulative injection](image-url)
Figure 9. Distribution of partial correlation coefficient for dependence $\Delta RF - \nu$

Figure 10. Cross-section of $\Delta RF$ surface by plane that is parallel to “variation coefficient” $\nu$ axis at $C = 6 \text{ kg/m}^3$, $V_{inj} = 600 \text{ m}^3$

The same way can be used to change from particular estimation to more common one (in case of slices by other coordinates). The means of estimation will be
histograms of distribution of partial correlation coefficient for different slices. They are illustrated on 11, 12 figures.

Figure 11. Distribution of partial correlation coefficient for dependence $\Delta RF - C$

Figure 12. Distribution of partial correlation coefficient for dependence $\Delta RF - V_{\text{inj}}$
Partial correlation coefficients for dependences $\Delta RF - C$ и $\Delta RF - V_{inj}$ on average are 0.95 and 0.945. It is evidence of extremely close connection [6].

After that, as a consequence of analysis of numerical experiment results, there were introduced a complex parameter $C_x$ that was function of permeability heterogeneity of object ($v$), technological parameters of realization ($C$, $V_{inj}$) and fluids properties ($\mu_w/\mu_o$):

$$C_x(C, v, V_{inj}, \frac{\mu_w}{\mu_o}, STOIIP) = \frac{C \cdot V_{inj} \cdot \frac{\mu_w}{\mu_o}}{STOIIP \cdot v},$$

(5)

where $C_x$ – complex parameter, kg/m$^3$.

This parameter allows taking into account geological variance, parameters of technology realization and physical and chemical fluids properties. Also $C_x$ can be done dimensionless by changing the volume concentration into mass one [7].

As a result experimental relationships between dimensionless oil recovery factor variance $\Delta RF$ and complex parameter $C_x$ were derived. They are pictured on figure 13.
Figure 13. Curves assemblage $\Delta RF - Cx$
Physical sense of points on each curve from this assemblage is a ratio of incremental oil production to initial geological reserves after diverter technology application under given parameters of realization (concentration, injected volume). Each line describes efficiency of technology application under geological conditions which are characterized by variation coefficient of lateral permeability $v$.

The sense of this express method is the possibility of approximate estimation of technological efficiency without a complex set of input data. It only requires minimal input dataset and time costs.

There are main assumptions accepted under derivation of these relationships:
- action efficiency is only defined by parameters that affect efficiency most strongly [5];
- reservoir model is layer-heterogeneous, without crossflow in z-direction ($k_z = 0$);
- viscosity of polymer solution is identically defined by its concentration and when there is partial mechanical destruction of one this relationship will be linear [1];
- method does not take into account mixing parameter that characterizes segregation between the water and the injected polymer solution [8] (model studies were being run under assumption that one was 0.5 fr.);
- flooding pattern weakly affect flow redistribution; behavior of water-cut is only defined by fraction of high-permeable channels [1].

**Findings**

Design of every geological and technological action must include forecast studies and it requires certain conditions (technological and economic). This express-method is suggested to use for approximate estimation of technological efficiency. In case of action viability it is recommended to make a decision about runs in detail with help of hydrodynamic simulation tools that allow opportunity more precisely to take into account reservoir heterogeneity, to get rid of accepted assumptions and to reduce risks.

Also it is necessary to understand that economic efficiency of this action will consist of not only incremental oil production but also of water production reduce, decrease of costs for gathering and treatment of oil. It is possible to reproduce these effects above from technology application only with help of hydrodynamic simulation studies.
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