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HYDRODYNAMIC SIMULATION OF RESERVOIR FLUIDS FILTRATION AT DIVERTER TECHNOLOGY CONDITIONS

ГИДРОДИНАМИЧЕСКОЕ МОДЕЛИРОВАНИЕ ПРОЦЕССОВ ФИЛЬТРАЦИИ ПЛАСТОВЫХ ФЛЮИДОВ ПРИ РЕАЛИЗАЦИИ ПОТОКООТКЛОНЯЮЩИХ ТЕХНОЛОГИЙ

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Abstract. There were base equations of mathematical physics for three-component flow case (oil, water, polymer). It was required to simulate diverter technology application and simulation approach of this technology. Approximate estimation algorithm for high-conductive pore volume was shown. It is based on history production data.

Also synthetic hydrodynamic model was built to estimate technological and economic efficiency of address diverter technology application. The results of technological and economic efficiency estimation were presented. There was the reason of quarter pattern failure comparing to entire model cell of flooding. Injectivity profiles for without-diverter technology and application technology cases were shown. It was illustrated as discrete after-application time dependence. These profiles described change of vertical sweep efficiency and they were evidence of injection profile smoothing. Also studies about influence of well shut-in time on oil recovery efficiency were conducted. Based on results of numerical study and theoretical assumptions, it gave the recommendations to increase success of method.

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 to take into account some of moments during the model building, history matching and making forecast variants.

Аннотация. В работе рассмотрены основные уравнения математической физики для случая течения трехкомпонентной смеси (нефть, вода и полимер), необходимые для моделирования применения потокоотклоняющих технологий (ПОТ), изложена методика моделирования данной технологии. Предложен алгоритм оценки высокопроводящего объема пор в первом приближении. Данный алгоритм основывается на промысловых данных работы скважин.

Также построена синтетическая гидродинамическая модель для оценки технологической и экономической эффективности точечного применения потокоотклонения, дизайна геолого-технических мероприятий. Представлены результаты расчета по технолого-экономической оценке метода. Приведено обоснование несостоятельности модели (для анализа выработки) четверти элемента разработки в сравнении с моделью целого элемента. Отображены профили приемистости нагнетательной скважины без применения технологии и по истечении различного времени после применения. Данные профили характеризуют изменение коэффициента охвата по мощности пласта, а также свидетельствуют о выравнивании профиля. Также были проведены исследования по изучению влияния времени остановки скважины перед закачкой раствора полимера. На основе анализа результатов численного эксперимента и теоретических предпосылок даны рекомендации для проведения мероприятий с целью повышения успешности ГТМ.

Данная работа будет полезна инженерам-нефтяникам при планировании ГТМ, прогнозировании эффекта и расчете технологической и экономической эффективности. Также она полезна для инженеров в сфере гидродинамического моделирования для учета некоторых моментов при создании, адаптации моделей под историю и расчете прогнозных вариантов при планировании ГТМ.

Keywords: hydrodynamic simulation, mathematical simulation, diverter technologies, polymers, polymer flooding, filtration flows, efficiency prediction.

Ключевые слова: гидродинамическое моделирование, математическое моделирование, потокоотклоняющие технологии, полимеры, полимерное заводнение, фильтрационные потоки, прогнозирование эффекта.

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. Use of geology and up-to-date hydrodynamic simulation may significantly improve efficiency of enhanced oil recovery methods. Also it is important to define both technological and economic efficiency. Review of publications shows that usage of up-to-date geology and hydrodynamic simulation technologies allows reaching increase of success ratio of physical and chemical methods application to 90% [1].

Equations of mathematical physics for three component flow (oil, water, polymer) are described by following equation system [2]:

$$\frac{d}{dt}\left(\frac{VS_o}{B_r B_o}\right) = \sum\left[\frac{Tk_{ro}}{B_o \mu_o}\left(\delta P_o - \rho_o g D_z\right)\right] + Q_o, \quad (1)$$

$$\frac{d}{dt}\left(\frac{VS_w}{B_r B_w}\right) = \sum\left[\frac{Tk_{rw}}{B_w \mu_{weff} R_k}\left(\delta P_w - \rho_w g D_z\right)\right] + Q_w, \quad (2)$$

$$\frac{d}{dt}\left(\frac{V^* S_w C_p}{B_r B_w}\right) + \frac{d}{dt}\left(V \rho_r C_p^a \frac{1-\phi}{\phi}\right) = \sum\left[\frac{Tk_{rw}}{B_w \mu_{peff} R_k}\left(\delta P_w - \rho_w g D_z\right)\right] C_p + Q_w C_p, \quad (3)$$

$$P_o = P_w + P_{cow}, \quad (4)$$

$$S_w + S_o = 1, \quad (5)$$

$$V^* = V(1 - S_{dpv}), \quad (6)$$

where V – cell pore volume, m^3;

S_o – oil saturation, dimensionless;

B_r – rock formation volume factor, dimensionless;

B_o – oil formation volume factor, dimensionless;

$\sum$ – the sum over neighboring cells;

T – cell transmissibility, µm^2*m^2/m;

k_{ro} – oil phase relative permeability in water-oil system, dimensionless;

δP_o – oil phase pressure drop between neighbor cells, Pa;

δP_w – water phase pressure drop between neighbor cells, Pa;

ρ_o – oil phase density, kg/m^3;

ρ_w – water phase density, kg/m^3;

g – acceleration of gravity, g= 9,81 m/s^2;

D_z – cell center depth, m;

μ_o – dynamic oil phase viscosity, mPa*s;

Q_o, Q_w – rates respectively for oil and water under stock tank conditions, m^3/day;

S_w – water saturation, dimensionless;

B_w – water formation volume factor, dimensionless;

k_{rw} – water phase relative permeability in water-oil system, dimensionless;

$\mu_{w\,eff}$ – effective viscosity of water in presence of polymer, mPa*s;

$\mu_{p\,eff}$ – effective viscosity of polymer solution, mPa*s;

R_k – the relative permeability reduction factor for the aqueous phase due to polymer retention, dimensionless;

V^* – the pore volume available for polymer, m^3;
C_p – polymer concentration in the aqueous phase, kg/m^3;
ρ_r – rock density, kg/m^3;
C_p^a – polymer adsorption concentration, kg/m^3;
ϕ – porosity, dimensionless;
S_{dpv} – dead pore space within each grid cell, dimensionless.

The Todd-Longstaff technique is required to calculate fluid viscosities. This method allows taking into account the effects of piston-like displacement on the leading edge of polymer surface and tongue effects on the lagging one.

There are some formulas to calculate effective fluid viscosities [3]:

$$\mu_{p\,eff} = \mu_m\left(C_p\right)^{\omega} \cdot \mu_p^{1-\omega}, \tag{7}$$

$$\mu_{w\,e} = \mu_m\left(C_p\right)^{\omega} \cdot \mu_w^{1-\omega}, \tag{8}$$

$$\frac{1}{\mu_{weff}} = \frac{1-\bar{C}}{\mu_{w\,e}} + \frac{\bar{C}}{\mu_{p\,eff}}, \tag{9}$$

$$\bar{C} = \frac{C_p}{C_{p\max}}, \tag{10}$$

where $\mu_m(C_p)$ – the viscosity of a fully mixed polymer solution as an increasing function of the polymer concentration (as a table), mPa*s;

μ_p – the viscosity of the solution at the maximum polymer concentration $C_{p\ max}$ (equals injected concentration), mPa*s;

$\mu_{w\,e}$ – partially mixed water viscosity, mPa*s;

ω – miscibility parameter characterizing separation (segregation) ratio, dimensionless;

$\bar{C}$ – effective saturation for the injected polymer solution within the total aqueous phase in the cell, dimensionless;

$C_{p\ max}$ – the maximum polymer concentration $C_{p\ max}$ (equals injected concentration), kg/m^3;

Equation (1) expresses the mass conservation law for oil, (2) – for water, (3) – for polymer. Expressions (4), (5) with boundary, initial conditions and PVT-properties enclose the non-linear equations system. The second term of the left-hand expression part (3) is a adsorption isotherm form of Lengmuir equation. As we can see from equations, important parameter that influence on the technology efficiency is the effective polymer concentration in water phase and, therefore, the volume of injected solution.

Synthetic hydrodynamic model of polymer flooding was built to estimate efficiency of technology application. This model had high heterogeneity through the lateral permeability (figure 1).

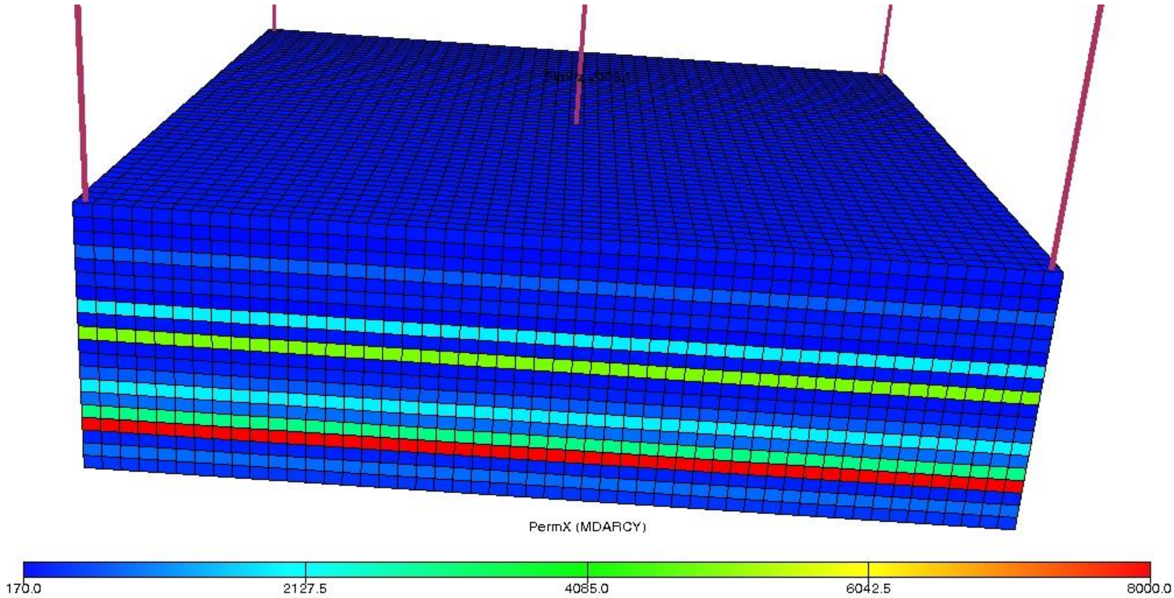

Figure 1. The view of model and lateral permeability

The distance between producer and injector equals 500 m and entire reservoir thickness was perforated (figure 2).

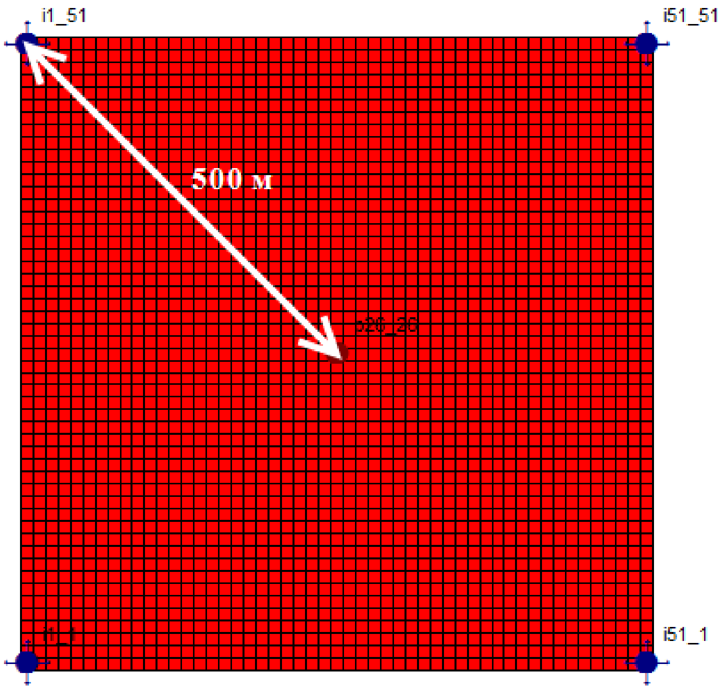

Figure 2. Horizontal model view

The decision about entire scale simulation of development pattern (not quarter as from symmetry principle) was accepted based on account of flow redistribution through area between wells (in case of quarter pattern there will be only 2 wells).

Second type boundary conditions were set up [4] (no flow across boundary). Initial conditions [5]: equilibration algorithm with usage of pseudo-capillary pressures and explicit definition of saturation and pressure cubes.

To do approximate estimation of high-conductive pore volume it may conduct analysis of (water-oil ratio) - (cumulative oil production) plot. Example was presented below on the figure 3.

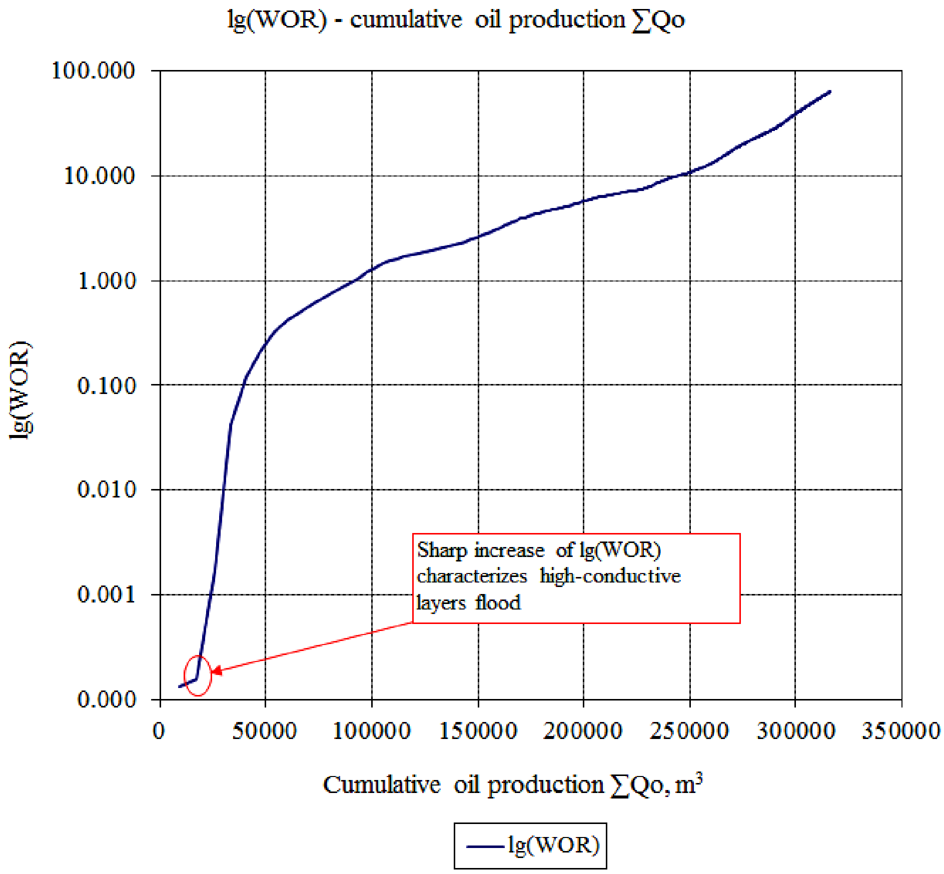

Figure 3. Water-oil ratio - cumulative oil production plot

Thus, high-conductive pore volume equals 8390,8 m3 for entire model and per 1 well this volume equals quarter of entire one - 2097,7 m3.

After that, injection of polymer solution was being conducted on one of injectors under defined properties derived from experiment (as an example - half part of high-conductive pore volume 1050 m3). Length of action effect during technology realization was 456 days with 570,10 m^3 incremental oil production. In this case polymer concentration was 3 kg/m^3. Net present value for action was 1,4 mln rub., profitability index – 6. As a result, incremental oil production and decrease of water on reactive producer have main impact on the economic profit.

There is a plot of oil rate as a time function for application case and without-application case (base variant) on the figure 4. The map of residual oil saturation is shown also (figure 5). As we can see from figure 5, the drainage zone of second element quarter has better reserve recovery due to increase vertical sweep efficiency and flow redistribution. It would not correctly estimate this effect during analysis quarter of development pattern.

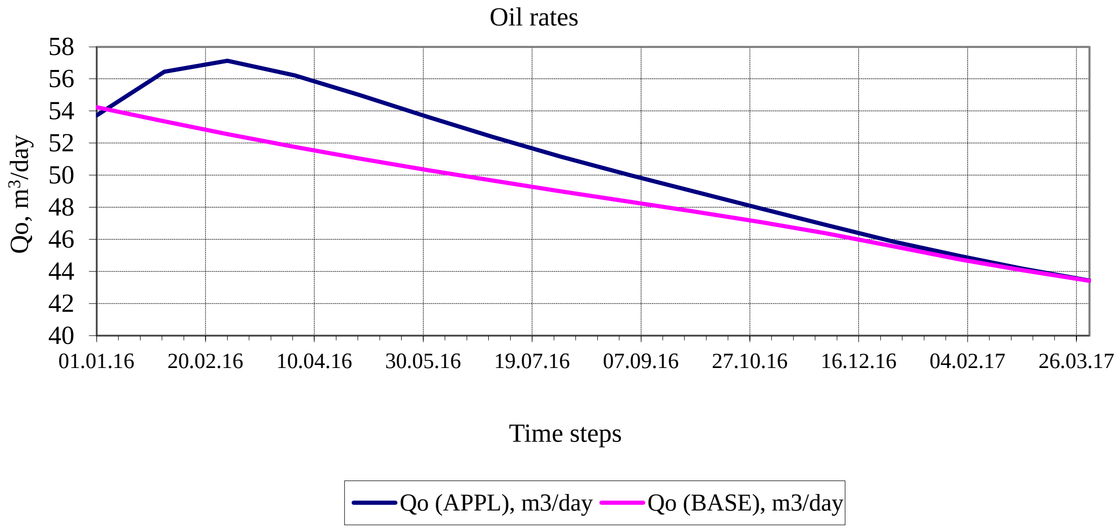

Figure 4. Comparison of oil rates for two variants: base and application of diverter technology

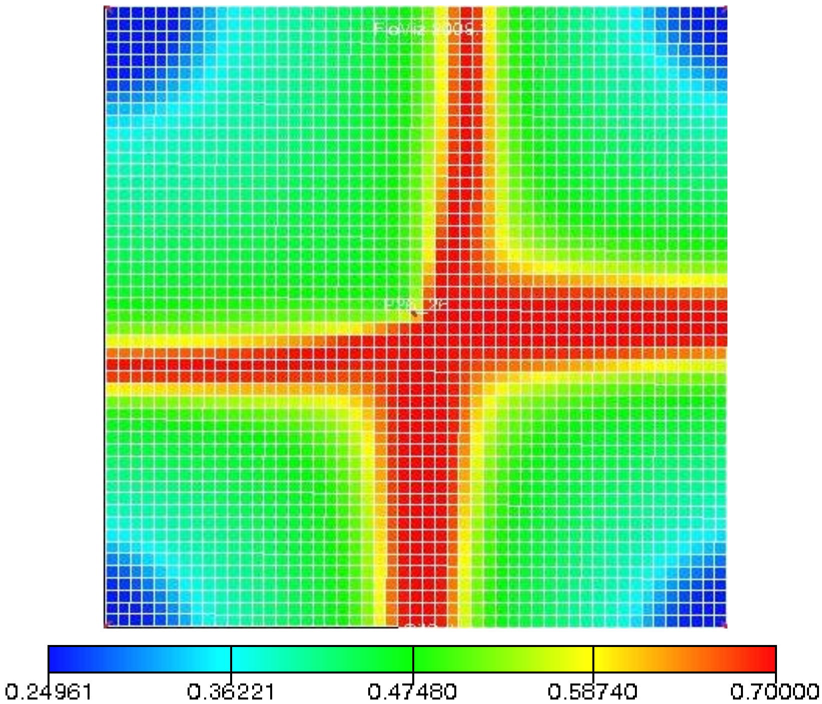

Figure 5. Map of residual oil saturation for diverter technology model

Figure 6 shows injectivity profiles of treated well at different times (without treatment, 1st week, 1st month after treatment) to analyze vertical sweep efficiency. Also it shows us that 17th layer, that has the highest permeability and water saturation (due to it has been flooded), decreases itself injectivity 6 times and low-permeable layers start to filter.

Thus, application of diverter technology smoothes injectivity profiles and increase vertical sweep efficiency under non-uniform permeable stratum conditions.

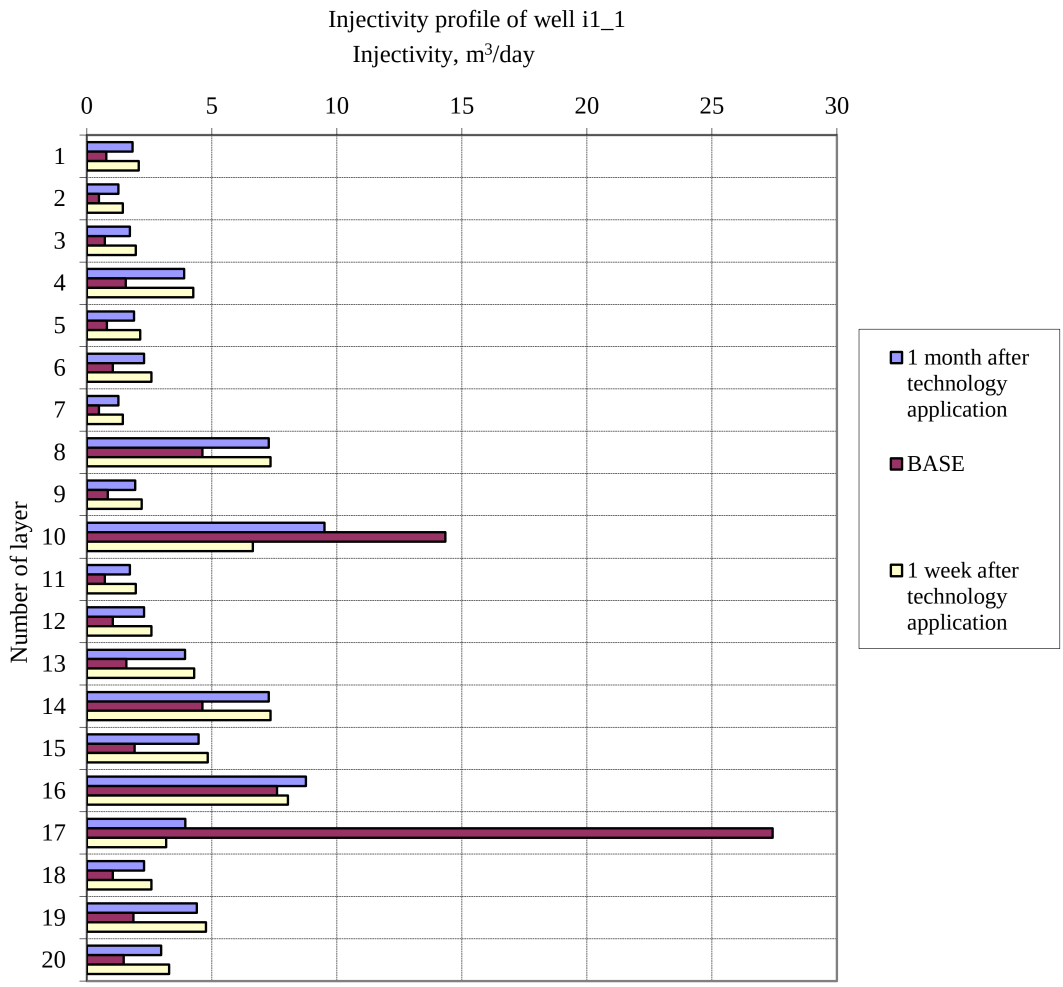

Figure 6. Injectivity profile before and after treatment

Also investigations about influence of well shut-in time were conducted. It is provided to stop injector to do pressure drop through layers: in high-permeable layers pressure will decrease faster due to they have bigger formation pressure conductivity factor [8]:

$$\chi = \frac{k}{\mu \beta^{*}}, \qquad (11)$$

$$\beta^{*} = \beta_m + m\left[S_w \beta_w + S_o \beta_o\right], \qquad (12)$$

where χ – formation pressure conductivity factor, м^2/с;
μ – dynamic phase viscosity, mPa*s;
β^* – formation storativity, 1/Pa;
S_{ph} – phase saturation $ph=[w,o]$;
β_{ph} – phase compressibility $ph=[w,o]$, 1/Па.

From formulas (11), (12) it can be seen that pressure will have dropped faster in high-permeable and water saturated layers than in low-permeable and oil saturated ones.

Figure 7 represent the main results of investigation about influence of well shut-in time before polymer injection. It is seen that active pressure reduction in high-permeable layers happens at first days. Also pressure drop is seen in low-permeable, but one is less active.

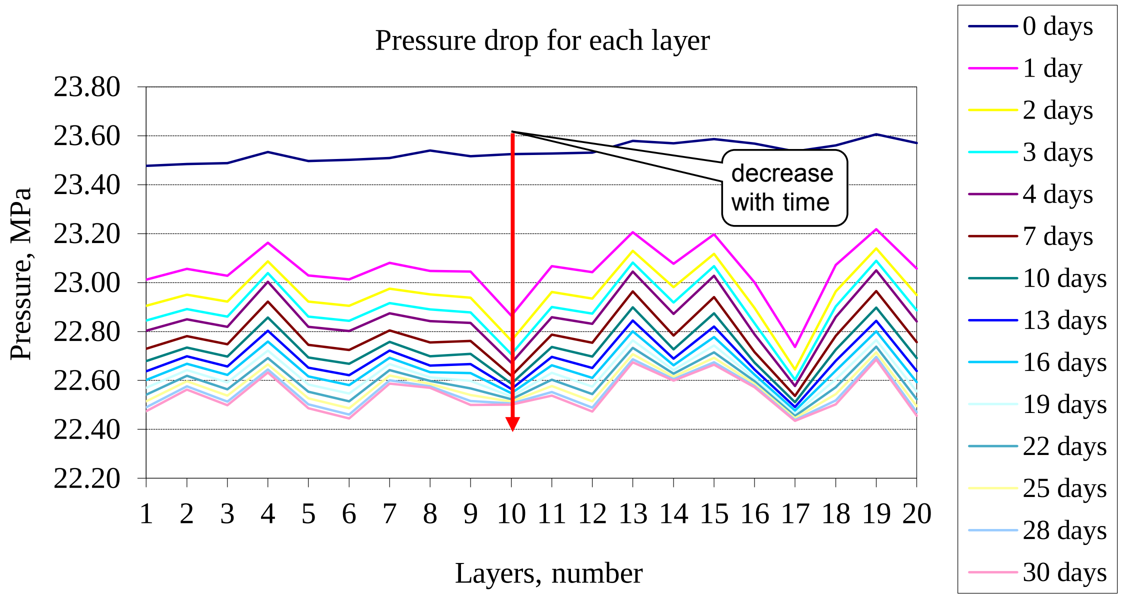

Figure 7. Pressure drop for each layer as dependence on time

Thus, it should be noted that long well shut-in time is not expedient both economic viewpoint (oil is not produced) and technological viewpoint – this time is enough to equilibrate pressure according to hydrostatics. Because of it polymer will invade in low-permeable layers easier. As a result the optimum well shut-in time under current conditions of this geological model is 1 day.

Findings

Design of every geological and technical action must include accurate objectivation of forecast values. It is can be done with help of mathematical simulation means much accurately. In this paper hydrodynamic simulation technique for design of diverter technology application was presented. It becomes possible to get a quantitative estimation of technological and economic efficiency with help of numerical experiment. Also algorithm for approximate estimation of solution volume that needs to fill high-conductive pore volume was suggested. Under conditions of current model it equals 2097,7 m^3. Also based on conducted studies about influence of well shut-in time before polymer injection, the recommendations for diverter technology realization were given.

References

1. Optimization of field development of JSCo "Gazprom Oil" with application of physicochemical diverter technology / Knyshenko A.G. [etc]. // The new resource-saving technologies of subsurface management and enhanced oil recovery: international Technology Symposium. 2007. P. 246-253.
2. ECLIPSE Technical Description 2009.1 [Electronic resource]. 2009. 1696 p.
3. Todd, M. and Longstaff, W. The Development, Testing and Application of a Numerical Simulator for Predicting Miscible Flood Performance, SPE 3484, 1972. p.9.
4. Aziz Kh., Settari A. Petroleum reservoir simulation. M.-Izhevsk: institute of Computer Science, 2004. 416 p.
5. Kanevskaja R.D. Mathematical simulation of hydrodynamic processes under hydrocarbon fields development. M.-Izhevsk: institute of Computer Science, 2002, 140 p.
6. Gafarova Z.R., Tasmuhanova A.E. The economic objectivation for ways to improve the efficiency of oil and gas companies: instructor's Manual for laboratory work. Ufa: publishing house USPTU, 2008. P. 3-9.
7. Shherbakov V.A., Shherbakov N.A. Evaluation of Enterprise (Business): instructor's Manual. M.: Omega-L, 2006. 288 p.
8. Shhelkachev V.N. Fundamentals and applications of the unsteady filtration theory: monograph in 2 parts. M.: Oil and Gas, 1995. Part 1. 586 p.

Литература

1. Оптимизация разработки месторождений ОАО «Газпром Нефть» с применением физико-химических потокоотклоняющих технологий / Кнышенко А.Г. [и др.] // Новые ресурсосберегающие технологии недропользования и повышения нефтеотдачи: междунар. технологический симпозиум. 2007. С. 246-253.

2. ECLIPSE Technical Description 2009.1 [Электронный ресурс]. 2009. 1696 с.

3. Todd, M. and Longstaff, W. The Development, Testing and Application of a Numerical Simulator for Predicting Miscible Flood Performance, SPE 3484, 1972. с.9.

4. Азиз Х., Сэттари Э. Математическое моделирование пластовых систем. М.-Ижевск: ин-т компьютерных исследований, 2004. 416 с.

5. Каневская Р.Д. Математическое моделирование гидродинамических процессов разработки месторождений углеводородов. М.-Ижевск: ин-т компьютерных исследований, 2002. 140 с.

6. Гафарова З.Р., Тасмуханова А.Е. Экономическое обоснование путей повышения эффективности деятельности нефтегазодобывающих предприятий: учебно-методическое пособие к выполнению лабораторных работ. Уфа: изд-во УГНТУ, 2008. С. 3-9.

7. Щербаков В.А., Щербакова Н.А. Оценка стоимости предприятия (бизнеса): учеб. пособие. М.: Омега-Л, 2006. 288 с.

8. Щелкачев В.Н. Основы и приложения теории неустановившейся фильтрации: монография в 2 ч. М.: Нефть и Газ, 1995. Ч.1. 586 с.

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