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Radial inflow model in the near-wellbore zone of exploitation wells*

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Abstract. The paper reviews the problem of forecasting the possible maximum pressure at the well-head, at the well-bore and at near-wellbore zone of reservoir during the process of new stimulation technology like reactive chemistry application. The technology provides stimulation by thermobaric effects. This impact occurs as a result of thermal decomposition of a binary systems at different reservoir conditions.

A necessary part of the solution of a more complete extraction of the reserves with a maximum economic profit is mathematical modeling. Since the 60-s of the created mathematical geological models of fields, examine the effectiveness of mining methods, the development of software systems of finding the ways to increase the oil recovery on the basis of mathematical modeling. Without computing the progress in this area is impossible, because analytical methods of solution are restricted by the consideration of simplified cases with a high degree of symmetry or give approximate estimates for nonlinear problems. At present there is a number of methods for solving a wide class of problems of subsurface hydromechanics, their properties being investigated as well as the legality of their use [1]. Based on existing and well proven methods of solution developed a large number of software packages for modeling various aspects of the process of the field development with the aim of predicting their characteristics and working parameters of modern engineering devices. Along with the domestic complexes of the programs GEOPAK (Sibniinp, Tyumen), SUTRA and LAURA (VNIIneft', Moscow), Weatherford (Weatherford), Moscow, TimeZYX (the group "trust"), HydroGeo (TPU), T-Navigator (Dinamics RF, Moscow) known in Russia and wide-spread foreign software packages Property, ECLIPS, and SIS PETREL (Schlumberger), RMS IRAR, Irap and TEMPEST MORE (ROXAR), VIP (Halliburton), Stratamodel, Total Drilling Performance (Landmark), SKUA/GOCAD Engineering Modeling (Paradigm Geophysical), Tigress (Geotrace Tigress Software).

Despite the existence of the software packages for solving tasks created on the basis of the well-developed theory and gained experience of successful application of the solution methods when creating new technologies, based

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on fundamentally new principles, requires a special approach. This paper presents a mathematical model and results of the thermogaschemical impact of the binary composition technology (TGHV BC) as applied in the wells. A mathematical model and a high-speed computation module have been developed to simulate studying parameters of the ongoing industrial tests by technological services of service providers. The most important physical processes based on the analysis of the simulated technology are extracted: the sequential chemical injection, reaction initiation, heating and formation of a zone of a high pressure in the course of the reaction, the distribution of temperature field and pressure field in the reservoir. The algorithm of calculation of the ongoing full-scale tests has been constructed the actual parameters of the reservoir and the injected reagents to a common metric are given. Taken into account the possibility of changing the input parameters of the reservoir and the injected substances, a convenient intuitive interface to output the results of the calculation graphically has been created. The results of the simulation and the full-scale tests LLC "LUKOIL-Komi", based on real parameters of the reservoir and the injected reagents, in the Permian-Carboniferous reservoir of the Usinsk field are presented.

1. The technology TGHV BC

The technology TGHV BC [2] provides the effect on the near-wellbore and remote zones of production reservoir by injection well of an inorganic salts solution binary composition, followed with the reaction of decomposition of the binary systems in porous-fractured of reservoirs. As a result of the binary system decomposition the high temperature (up to 300–320°C) and pressure are generated thus heating rocks and high-viscosity hydrocarbons and cracking the reservoir [3, 4].

In most cases, the injection is performed through a tubing into the far zone of production reservoir, standard pumping equipment is used. Also TGHV BC technology provides ability to perform treatment through the annuls (without removing downhole pumping equipment) as binary systems are neutral and reaction occurs at the remote zone of reservoir, so in that case there is no impact on the downhole equipment.

The control of real time processing of the reaction on the bottom of a well is performed using a high temperature measurement system, and the rate of decomposition and the reaction temperature may be regulated by the concentration of salts. The result of the thermogaschemical impact on the bottomhole formation zone is the permeability reconditioning, recovery thinning out the crude and the formation of additional filter channels. The technology has been developed by specialists of LLC "CNT", protected by the Russian and foreign patents, passed the examination for industrial safety in the licensed enterprise JSC Vzryvispytaniya.

2. A mathematical model

The selected one-dimensional multi-phase model of filtration processes describes the radially symmetric distribution of substances in a porous medium from a point source [5]. The algorithm for calculating the parameters of the ongoing field testing consists in determination of coordinates of the reaction zone and calculating the distribution of the temperature field and the pressure field in the reservoir. The process of displacement is described as a radial distribution of reagents piston method. We solve the heat conduction equation with variable coefficients in the cylindrical coordinates:

$$\frac{\partial T}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\Big(k_T r \frac{\partial T}{\partial r}\Big), \quad T(r,t)_{t=0} = T_0(r),$$

where T is the temperature, $k_T = k_T^l + m_r k_T^r$ is the thermal diffusivity, which consists of the values for oil/water k_T^l and rock k_T^r with a given porosity m_r. The thermal diffusivity $k_T^{l,r} = \frac{\lambda^{l,r}}{c^{l,r}\rho^{l,r}}$, where $\lambda^{l,r}$ is the thermal conductivity, $c^{l,r}$ is the heat capacity, $\rho^{l,r}$ is the density, is determined from the actual surface conditions.

Knowing the exact radial distribution of porosity and other reservoir parameters it is possible to develop a full hydrodynamic interaction model [6, 7] of the reagents propagation in the reservoir with the details of the calculation of pressure, density, velocity, saturation, specific gravity, etc. To estimate the resulting pressure in the reservoir it is sufficient to calculate the formation-pressure conductivity equation:

$$\frac{\partial P}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\Big(\chi \frac{\partial P}{\partial r}\Big), \quad P(r,t)_{t=0} = P_0(r).$$

Here P is the pressure, $\chi = \frac{k_r}{\mu(m_r\beta_l + \beta_r)}$ is the pressure conductivity factor, k_r is the permeability, μ is the viscosity, β_l, β_r are the coefficients of compressibility of the substance and layer. The coefficient of the compressibility of a substance is equal to the water compressibility coefficient for the region around the wells, of the reagent compressibility in the reaction zone, the combination of the coefficients of compressibility of water and oil in the inactive layer (s is the share of oil in the reservoir). The compressibility factor of the reservoir is taken for Sandstone $\beta_r = 10^{-9}$ ms^2/kg.

The layer temperature and pressure (known as a result of the full-scale measurements) in the reaction zone (directly calculated from the data on the injected reagents) are selected as initial data. The Dirichlet conditions are set on the boundaries. The size of the computational domain, the hydrodynamic reservoir characteristics (porosity, permeability, reservoir pressure, reservoir capacity, density, volume of injection, the compressibility coefficient, viscosity and thermal diffusivity) are user-specified. The time step is calculated using the user-specified parameters.

The discrete model [8] keeps the properties of the continuous problem used for finding the temperature and pressure. The difference scheme [9–11] is completely conservative and uniformly stable in the initial data in the energy grid normal. The algorithm implementation consists of two explicit solvable steps.

3. The thermochemical reaction

Let us consider the reaction

$$NH_4NO_3 + NaNO_2 \longleftrightarrow NH_4NO_2 + NaNO_3,$$

where NH_4NO_3 is the ammonium nitrate, $NaNO_2$ is the sodium nitrite, NH_4NO_2 is the ammonium nitrite, $NaNO_3$ is the sodium nitrate. The amount of heat generated by the combustion of binary compositions is calculated using the relationship $Q_T V = (T_{\max} - T_0) M k_T$, where Q_T is the heat (kcal/m^3) for heating the volume V in cubic meters, $T_{\max}$ is the temperature in the reaction zone, T_0 is the temperature in the reservoir, M is the mass of solution, and k_T is the heat capacity of the solution.

The algorithm allows one to determine the BC temperature $T_{\max}$ at the completion of the reaction time, the generated heat Q_T, the volume of evolved gas, from the volume of injection and the percentage of salts in the BC. The algorithm used allows one to determine the data for any reasonable percentage of salts. Knowing the BC temperature $T_{\max}$ at the completion of the reaction time, porosity and permeability, it appears possible to calculate heat losses per heating the layer. Thus, it is possible to accurately determine the initial temperature distribution.

4. Simulation of the technology TGHV BC in the wells of the Permian-Carboniferous reservoir of the Usinsk field

The Usinsk oil field is located in the Komi Republic. It is part of the Timan–Pechora province. The permocarbon oil reservoir was found in 1968, and was brought into operation in 1977. The permocarbon reservoir of the Usinsk Deposit has a complex geological structure. The quasi-viscous oil, considerable thickness and heterogeneity of the reservoir are the main features of geological and physical characteristics.

Unfortunately, at the present time it is impossible to determine a priori estimates for the process of temperature and pressure distribution in the layer depending on the mass and the flow rate. Therefore, necessary data can be obtained only by carrying out a series of numerical experiments, solving a series of direct problems. Currently, the model is a working tool for the simulations on TGHV BC. Using the proposed mathematical model, Optimal injection schedule

Stage	Injected fluid	Liquid volume, m^3
1	BC injection	30
2	Buffered water injection	5
3	Hydrochloric acid 12 % injection	12
4	Displacement water injection	20
5	Pump stop	

specialists of LLC "CNT" have carried out preliminary calculations and conducted full-scale tests in the Permian-Carboniferous reservoir of the Usinsk field, LLC "LUKOIL-Komi" [12].

The calculations have allowed finding the optimal schedule of injection (the table) for the well No. 3004 the Usinsk Deposit in which a maximum temperature at a distance of 25 m from the bottom (Figure 1) is greater than 250°C as a result of decomposition of BC (Figure 2). The temperature in the bottomhole zone is equal to 60°C after 9 hours and 75°C after 24 hours after the work completion.

On Feb 4–5, 2016 the field tests with the technology TGHV-BC for this well were carried out. Temperature and pressure were measured in the range of 1252–1397 m after completion of works. The well was closed in-waiting on carrying out chemical reactions to 24 hours.

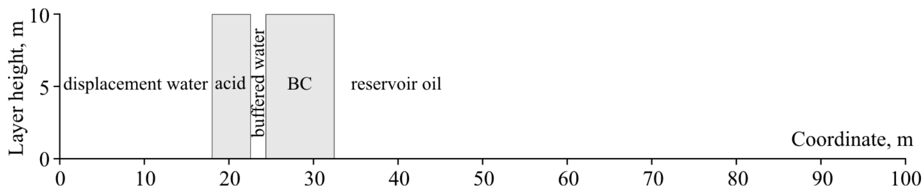

Figure 1. Radial concentration profile of BC

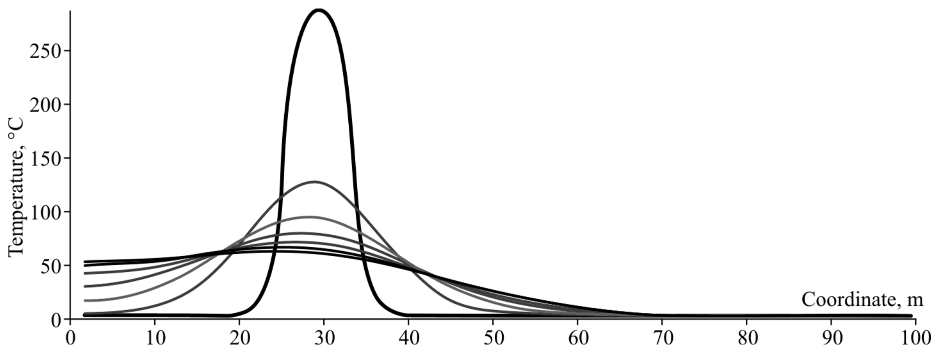

Figure 2. Thermal front of oil displacement at different instants time: 17 min, 4, 9, 13, 17, 21, 24 h

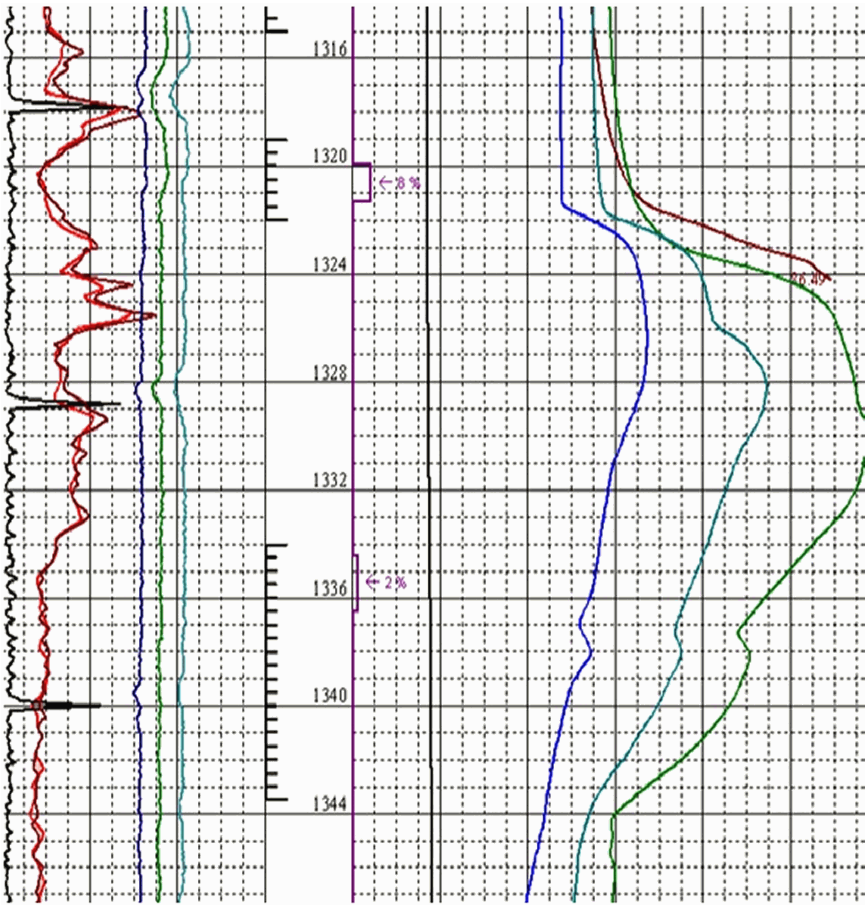

Figure 3. The results of thermometry

The analysis of thermometry after conducting TGHW (Figure 3) has shown that, after 9 hours, the temperature is fixed at around 55–60°C in the bottom-hole formation zone (0–10 m). The data obtained correspond to the calculated temperatures (see Figure 2).

Conclusion

The mathematical model of the technology thermogaschemical effects of the binary structure on the well is proposed. The experience gained in applying the software package in the Permian-Carboniferous reservoir of the Usinsk field, LLC "LUKOIL-Komi", shows the working accuracy of the work prediction of the complex impact on bottom-hole zone of the productive stratum of the injected binary chemical systems (monopropellant) based on inorganic salts.

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