Prediction of sediment-forming technologies' effectiveness for enhanced oil recovery in West Siberian fields

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Abstract. The article presents the results of geological field analysis. The presented results showed that the application of methods to equalize the injectivity profiles of injection wells and to reduce the water cut of produced products is most effective with an average water cut of the production of wells. In this case, the maximum effects of the impact are observed on the layers of the third group. It was established that in the reservoirs of the first and second groups, which are at a late stage of development, the most significant effects are produced by flow diverting technologies associated with a large volume of injection of reagents.

1. Introduction

At oil fields in Russia and abroad, methods for increasing oil recovery based on increasing the coverage of formations by the effect of water flooding are widely used [1–6]. Such methods (technologies) include flow diverting technologies for increasing the degree of development of flooded layered and zonal heterogeneous productive formations. There are prospects for the application of such technologies to increase the oil recovery coefficient, recognized by the community of oil scientists and practitioners [7–11].

Initially, the technology of injection of gel-forming compounds into injection and production wells was considered as a geological and technological measure to reduce the water cut of the produced products. However, the accumulated field experience with the use of gelling agents has shown that by adjusting the injectivity profile of injection wells and reducing the return from water-washed zones in production wells, it is possible to influence the coverage factor of the reservoir by water flooding and, therefore, increase the oil recovery coefficient.

Reagents based on organic polymers, organ element compounds, inorganic substances and finely dispersed mixtures (clay powder solutions, wood flour) are used as gelling compositions. In one of the mechanisms of the process, gel formation in the formation occurs due to an increase in the temperature of the gel-forming compositions, i.e. reagents have selected that form a gel at reservoir temperature,
and are injected at a lower temperature without gel formation in the well. The second mechanism of gel formation in the reservoir is as follows: the polycondensation of molecules (they are crosslinking with the formation of a gel) is determined by the presence of ions, usually, metals, which are released from the gel-forming compounds due to specific reactions with salts and acids of the formation water. The technology for processing bottom-hole zones of a formation consists either in preliminary mixing of reagents at the mouth and forcing the mixture into the formation, or in the alternate injection of reagents into the formation and their in-situ mixing. After injection, the well stops to respond for 1-7 days. The reagent strand can be pumped into the entire section of the formation or selectively into selected sections of the productive section using packer devices.

In practice, the composition of the “Galka,” proposed by the group L.K. Altunina, has proven itself well. The main components of this gelling composition are aluminium chloride (AlCl₃) and urea (CO₇(NH₂)₂). A more convenient (liquid) form of such a composition is gel-forming compositions developed by the NIIINtefetrovich RV-3P-1.

2. Materials and methods
The proposed mathematical model of the process is the development of the theory of gel treatments. The development consists of taking into account the physicochemical characteristics of gelation of the reagent RV-3P-1.

For injection wells in a porous medium, the mobile phase is water and its solutions. We distinguish the following main components of the aqueous phase involved in the process: 1 – urea, 2 – ammonia, 3 – aluminium chloride, 4 – aluminium hydroxide.

The mass conservation equations for these components are:

$$ m \cdot \rho_1 \frac{\partial C_1}{\partial t} + \frac{1}{r} \frac{\partial}{\partial r} (r \cdot m \cdot \rho_1 \cdot v_1 \cdot C_1) = -J_{12}; $$

$$ m \cdot \rho_1 \frac{\partial C_2}{\partial t} + \frac{1}{r} \frac{\partial}{\partial r} (r \cdot m \cdot \rho_1 \cdot v_1 \cdot C_2) = J_{12} - J_{24}; $$

$$ m \cdot \rho_1 \frac{\partial C_3}{\partial t} + \frac{1}{r} \frac{\partial}{\partial r} (r \cdot m \cdot \rho_1 \cdot v_1 \cdot C_3) = -J_{34}; $$

$$ m \cdot \rho_1 \frac{\partial C_4}{\partial t} + \frac{1}{r} \frac{\partial}{\partial r} (r \cdot m \cdot \rho_1 \cdot v_1 \cdot C_4) = -J_{34} + J_{24}, \quad (1) $$

where $\rho_1$ is the density of the aqueous phase; $v_1$ – its speed; $J_{ij}$ are the rates of the corresponding reactions; $r$ and $t$ are the radial coordinate, measured from the centre of the well, and time.

Considering it fair that the volume of substances entering into the reaction is equal to the volume of the obtained reagents, we can determine the water velocity through the rate of fluid injection into the well:

$$ Q = 2\pi \cdot r \cdot h \cdot m \cdot v_l \quad \text{or} \quad m \cdot r \cdot v_l = \frac{q}{2\pi \cdot h}; \quad (2) $$

where $Q$ is the flow rate of the fluid through the well, $h$ is the reservoir thickness.

The reaction rates $J_{ij}$ are determined from kinetic laws:

$$ J_{12} = m \cdot \rho_1 \frac{\partial C_2}{\partial t} = m \cdot \rho_1 \cdot Z_{12} \exp\left(-\frac{E_{12}}{RT}\right) C_1; $$

$$ J_{34} = m \cdot \rho_1 \frac{\partial C_4}{\partial t} = m \cdot \rho_1 \cdot Z_{34} \exp\left(-\frac{E_{34}}{RT}\right) C_3 \cdot C_4. \quad (3) $$

The temperature distribution in the bottom-hole zone of the well is determined from the equation of heat influx in a saturated porous medium:

$$ H_{ef} \frac{\partial T}{\partial t} + \frac{1}{r} \frac{\partial}{\partial r} (r \cdot H \cdot v_1 \cdot T) = 0, \quad (4) $$

where $H_{ef}$ is the volumetric heat capacity of a saturated porous medium; $H$ is the volumetric heat capacity of the aqueous phase.

The main stages of this technique are:
1. Determination of the amount and rate of injection of gelling compositions into each interlayer of a productive section through the hydroconductivity of the interlayers, the volume and rate of injection of gelling compositions into wells according to the formulas:

\[ Q_i = \frac{k_i \cdot h_i}{M_i} \sum_{j=1}^{N} \frac{k_j \cdot h_j}{M_j} \]

where \( Q \) is the injection rate; \( V \) is the injection volume of the reagent solution, the index “i” indicates the amount of reagent entering the \( i-th \) layer.

2. Determination of the amount of produced aluminium hydroxide (Al(OH)_3) and gel in each layer.

3. Calculation of the distribution of permeability of the interlayers in depth after the reaction – \( k_i(r) \).

4. Determination of the injectivity profile after processing according to the generalized Dupuis formula taking into account the changed permeability \( k_i(r) \).

The optimization of the process consists in calculating the injection volume of gel-forming compositions, which leads to a decrease in the total injectivity of the formation by no more than 25% of the initial one, with the maximum levelling of the injectivity profile after treatment.

For predict and analyze the results of the injection of the RV-3P-1 reagent, 14 injection wells of the Severo-Danilovsky field were selected. A preliminary study of the injectivity of the section in the wells was not carried out. Therefore, the GIS results were taken as the initial data for the calculations.

According to the method described above, the penetration radii of the gel-forming composition in the interlayers (R_i) were determined. An analysis of the prediction of the results of the treatment of wells with a gel-forming composition showed that the alignment of the injectivity profile increases with the growth of the reagent injection volume. Thus, the optimal injection volume is determined from the technological condition that after treatment, the total injectivity of the well should not fall below 60–70% of the initial value before the well was processed.

3. Results and discussion

The results of calculations of the differential profile of the injectivity of the well before and after treatment are presented. The results show that with weak heterogeneity of the formation, the gelling reagent is distributed more or less uniformly over the productive section and the degree of alignment of the injectivity profile is low. The optimal injection volume of the gel-forming compounds RV-3P-1 is about 2m³ per meter of productive formation thickness. With a significant heterogeneity of the formation, the maximum amount of gel-forming composition enters highly permeable layers and substantially blocks them. After exposure, non-accepting formation thicknesses begin to connect. Since the reagent enters mainly in the interlayers that need to be blocked, the reagent consumption decreases and amounts, in this case, to about 1m³ per meter of productive thickness.

The application of gel-forming technologies using aluminosilicates has been simulated using many deposits of the Sredneobskoye NGO developed by divisions of LUKOIL-Western Siberia LLC. The objects of the studied deposits were divided into three relatively homogeneous groups, each of which is represented by a typical object. Constructed geological and mathematical models of reservoirs are shown in Figure 1.

The first group of oil deposits is characterized by the most homogeneous formations (Figure 1). The viscosity of oil under reservoir conditions is 1.54 MPa·s. A typical object of this group is characterized by a maximum design oil recovery factor = 0.48. Injection wells are characterized by an injection rate of 100 m³ / day. The initial reservoir pressure was 23.9 MPa, and associated gases are in a dissolved state.

The second group of deposits is represented by the most permeable formations (Figure 1). A typical group object has in its section three main layers. The viscosity of oil in reservoir conditions at the test site is 1.11 MPa·s. Significant clay and heterogeneity factors result in a relatively low design oil recovery factor = 0.35. The average injection rate of injection wells in this group is maximum, for a typical object – 122.6 m³ / day. A breakthrough of water to the production wells closest to the
injection row results in relatively high water cut of the produced products in groups. The initial reservoir pressure at the facility was 24.0 MPa, the oil in the reservoir is in a single-phase state.

The reservoir is saturated with a light oil (viscosity 0.7 MPa·s). The design oil recovery factor is 0.35, i.e. recoverable reserves are planned to be extracted mainly from the last layer. Due to the high heterogeneity of the formation, a massive breakthrough of injected water is observed in the production wells closest to the supply circuit. The initial reservoir pressure at the test site was 29.0 MPa.

The in-line development system is considered, and the analysis is limited only by the injection and the first mining series. The filtration process between the discharge and production rows is modelled as part of a two-dimensional profile problem. The rate of injection and selection of fluid in the inlet and outlet sections is determined by summing the flow rates of the fluid in the injection wells and dividing by the cross-sectional area of the reservoir into the injection and production rows. Isolated layers are considered hydrodynamically unbound. In each layer, the filtration flow is considered to be one-dimensional. The initial state at the moment is the water cut of the extracted products of the first mining row 80%.

The effect of gel-forming compounds is modelled in two stages. At the first stage, the change in the injectivity profile of injection wells is calculated as part of the axisymmetric profile problem of injecting a gel-forming composition into the well and forming a gel in highly permeable interlayers using the Oil plus software package. Next, the waterflooding of model formations (flat profile task) with a modified injectivity profile of the interlayers after gel treatment is calculated. The results obtained to increase the oil recovery coefficient are predictive for the remaining sections of the reservoir when applying the recommended methods as they are developed.

The first task is to determine the volume of injection of the gel-forming composition into the well, leading to a minimum effect on the injectivity of low-permeability layers and maximum insulation of highly receptive layers washed with water. In the second task, the injectivity profile of the formation after gel exposure is determined. The result of the first task is necessary for the economic calculation of the costs of a one-time impact, the results of solving the second problem are laid as boundary conditions in the first model to predict the effectiveness of the treatments.

The process of filtering injected compositions and gel formation in the bottom-hole zone is described in the framework of the axisymmetric problem of filtering a multicomponent fluid in a reservoir, consisting of several unbound layers with different permeability and power. The system of
equations of the hyperbolic type being solved is solved by the method of characteristics. The pressure distribution in the reservoir is determined from the solution of the Laplace equation. The distribution of sediment in the n-th layer after complete gelation, after solution, has the form:

\[ A = (G-I) [C]_1 + \{ (C)_1^{\text{1/2}} + B(\text{S-1})/Q(\pi m h(r_2^2 - r_1^2) - V/G - I)^{1/2} \}; \]

\[ G = 1 + (1-m) \rho \cdot \Gamma / m \cdot \rho_c; \quad B = (C_2 f \alpha A, \]

where \( m_n, k_n, p_n \) – porosity, permeability and pressure in the n-layer, \( c \) – concentration of reagents in the stream; \( a_n \) is the gel concentration in a porous medium, \( j_n \) is the gelation rate; \( j \) and \( a \) are the adsorption rate and concentration of the adsorbed reagent; \( S_r, S_w \) – density of rock and water; \( \Gamma \) is Henry's constant; \( V, Q \) – volume and speed of the injection of the composition into the n-th interlayer. The values of these constants are determined by the initial injectivity profile of the reservoir model.

The presence of a gel in a porous medium affects the permeability of the layers. This effect can be taken into account by the Cozeny-Karman formula:

\[ k_{o/d} = (m_n/m_o^e) = (I-a_n)^e, \]

where \( e = 6 \) is an empirical parameter characterizing the geometry of the pore space and determined experimentally; \( m_o, k_o \) are the values of porosity and permeability of the n-th layer in the initial state before gel treatment of the formation, the function \( a_n \) is substituted from solution (7) for each layer taking into account the values of \( V_n \) and \( Q_n \).

\[ V_n = (V \cdot k_e h_o) / \Sigma V_c k_c h_c; \quad Q_n = (Q \cdot k_e h_o) / \Sigma Q_c k_c h_c, \]

where \( V, Q \) are the total volume and rate of injection of the gel-forming composition into the well.

The determination of the optimal injection volume is carried out according to an iterative algorithm until the achievement of the optimality criteria formulated above. The volume of injection of gel-forming compounds in the facilities is 64; 105 and 46 m³. The results of the calculations of this stage are shown in Table 1 and Figure 2.

The optimal consumption of reagents for the entire oil-saturated thickness for the layers of polygons of groups 1–3 are 64, respectively; 105 and 46 m³. The specific consumption of reagents per meter of productive thickness in the strata-polygons was 8; 10.5 and 2 m³. The predicted oil recovery coefficient is compared with the base case of full waterflooding. As can be seen from the above figures, the increase in oil recovery at the first two facilities is 4 points, and at the third facility – 2 points.

The next block of studies is devoted to predicting the effectiveness of sludge-forming technologies of enhanced oil recovery for the facilities of the Langepass group of fields. Three typical sites were identified using the grouping procedure.

The search for the optimal reagent volume for a particular well, which ensures the maximum alignment of the injectivity profile, is carried out by mass calculations of treatment parameters for various volumes of reagent pumping. Table 2 gives recommendations for injection volumes.

**Table 1.** The injectivity of the interlayers before and after the exposure to a gel-forming composition based on aluminosilicates on the injection well in formations with geological and mathematical models shown in Figure 1

| Group of layers | Pickup typical injection wells, t / day |
|-----------------|----------------------------------------|
|                 | 1           | 2           | 3           |
| Interlayers     |             |             |             |
| Before exposure | 20          | 80          | 36          |
| After exposure  | 26          | 74          | 48          |
|                 | 2           | 22          | 64          |
|                 | 3           | 10          | 90          |
|                 | 56          | 28          | 72          |
The mathematical model of the process includes balance equations for gelling components (gelling compositions based on liquid glass and RV-3P-1 reagent) and heat flow equations. Analytical solutions to the gelation problem in a single interlayer are obtained. The software product “GTM +” and the engineering forecasting technique are based on the following initial assumptions. When a gelling reagent is injected into the formation, its distribution over interlayers and interlayers occurs in accordance with the debitometry data prior to the impact (if any data are available) or well logging data on the conductivity of the interlayers. In each interlayer, the problem of gel precipitation during the injection of the reagent and shutdown of the well for response is solved, and the distribution of the gel over the depth of the layers is determined. Further, in each layer, pressure distributions are calculated, taking into account data on the distribution of the gel and changes in the porosity and permeability of the medium. After that, the ratio of induced pressure gradients in the bottom hole zone and the limiting gradient due to the plastic properties of the gel are checked.

It is believed that the gel is a stable and stationary system in the interlayers, where the pressure gradient does not exceed a critical value and fills part of the pore space. Otherwise, the gel barrier is considered unstable and is immediately washed out of the interlayer. Following the Kozeny-Karman relation on the relationship between porosity and absolute permeability, the depth permeability distributions are determined after treatment for interlayers with a stable gel barrier. The optimal volume of injected reagent is determined by mass calculations of the process of pumping various volumes of reagent rims based on the objective function – the maximum alignment of the flow profile over the thickness of the reservoir.

The calculations are the source data for determining the productivity of wells after exposure. The software product “GTM +” used allows predicting the injectivity profile after gel precipitation. The package also implements the task of determining the profile of water cut in the formation by

Figure 2. The dynamics of the oil recovery coefficient after exposure to gel-forming compositions on injection wells of reservoirs a) first, b) second, c) third groups. Curve 1 – basic waterflooding; curve 2 – based on aluminosilicates and hydrochloric acid.
vertical section, taking into account field data on water cut of the product, which allows predicting the change in the proportion of water in the produced product after exposure.

Table 2. Recommended injection volumes of reagents at the landfill facilities

| Group | Plast | Reagent | Volume, m³ |
|-------|-------|---------|------------|
| 1     | BV8, Uryevskoye field | RV-3P-1 | 85 |
|       |       | SPDS    | 1800       |
|       |       | ESS     | 44         |
|       |       | ESS + PKV | 40+30 |
|       |       | aluminosilicates | 180 |
|       |       | SPS + PKV | 150+42 |
| 2     | BV6, Stream field | RV-3P-1 | 90 |
|       |       | aluminosilicates | 200 |
| 3     | AB1 / 3, South Pokachaevskoye field | SPS + PKV | 80+20 |
|       |       | aluminosilicates | 100 |

An example of the results of calculating the change in the injectivity profile of a well for a model formation under the influence of ATP is shown in Figure 3. The calculations performed allowed calculating the optimal injection volumes of reagents, recommended injection volumes of reagents. The calculation results for changing the injectivity profiles of injection wells to predict additional oil production was laid down in the EOR program by introducing a skin effect in each layer.

Following the calculated skin effects, the process of water flooding and reducing the water content of the extracted products were calculated. Thus the effect of the impact was calculated by comparing with the results of water flooding without introducing the skin effect. Forecasts were made of the application of the effectiveness of enhanced oil recovery methods.

The forecast results for the use of stream-levelling technologies are shown in Table 3.

Figure 3. Change in the injectivity profile of the injection well while injecting 200 m³ SPS into the formation of the 3rd group into the model formation
Table 3. Forecast of the results of applying flow-leveling technologies to improve the waterflooding system

| Plast          | Reagent     | Volume, m³ | Additional oil production, tons per well-treatment | Type of wells being processed |
|---------------|-------------|------------|---------------------------------------------------|------------------------------|
| BV8 Uryevskoye field | RV 3P        | 85         | 400                                               | Discharge                    |
|               | SPDS         | 1800       | 1500                                              | Discharge                    |
|               | ESS          | 44         | 500                                               | Discharge                    |
|               | ESS+PKV      | 40+30      | 1200                                              | Discharge                    |
|               | aluminosilicates | 180      | 400                                               | Discharge                    |
| BV 6 Potochnoe field | SPS+PKV     | 150+42     | 1500                                              | Discharge                    |
|               | RV 3P        | 90         | 800                                               | Discharge                    |
|               | aluminosilicates | 200      | 800                                               | Discharge                    |
| AV 1/3 South Pokachavskoye field | SPS          | 200        | 2100                                              | Discharge                    |
|               | SPS+PKV      | 80+20      | 1800                                              | Discharge                    |
|               | aluminosilicates | 100      | 1200                                              | Discharge                    |

4. Conclusion
An analysis of the results showed that the use of methods to equalize the injectivity profiles of injection wells and to reduce the water cut of produced products is most effective with an average water cut of the product. Therefore, the maximum effects from the impact are observed on formations of group 3. In reservoirs of groups 1 and 2, which are at the last stage of development, the most significant effects are obtained by flow-leveling technologies associated with a large volume of reagent injection.

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