Forecast estimation of sandstone collectors transformation of Lower-Karmalinsky bituminous deposit during its development by the SAGD method

E Koroleva, A Bakhtina, A Eskin, E Barieva, A Koroleva

a Institute of geology and petroleum technologies, Kazan Federal University, Kazan, Russia
b Kazan State Power-engineering University, Kazan, Russia

e-mail: eskin.aleksey@gmail.com

Abstract. In order to increase hydrocarbon reserves in recent years, begun to actively involve natural bitumens in the development. On the territory of Tatarstan, one of the experimental sites for testing various technologies for the extraction of bitumen is the Lower-Karmalinsky bitumen deposit. Currently, on the field is testing the SAFD method. According to this technology for the extraction of hydrocarbons, steam is pumped in large volumes at a temperature of about + 180°C. Superheated steam reduces the viscosity of hydrocarbons, making them mobile. However, focusing on the reduction of bitumen viscosity, the problem of mineral phase’s transformation due to anthropogenic impact in reservoir is not taken into account. In this work, using thermodynamic modeling, it was shown that the injection of superheated steam into the formation of bitumen-saturated sandstone will lead to the dissolution of calcite cement. Moreover, depending on the salinity of the injected water in the form of steam, the dissolution of carbonates will occur at different temperatures. To improve the technological characteristics and to increase the recoverability of bitumen from reservoir, it is recommended to pump hot water with as little mineralization as possible into sandstone layers. Temperature intervals were established, which should be followed in the process of technological development of bitumen collectors at the stage of heating the reservoir and at the stage of extracting water-bitumen solutions.

1. Introduction

One of the priorities in the strategy for the development of oil regions is the involvement in the development of unconventional hydrocarbon resources. As part of this strategy, on the territory of the Tatarstan Republic, began to actively explore the possibilities of extracting shallow lying natural bitumen in the sediments of the Ufa low Permian tier [1,2]. Since 2006, in the pilot industrial development finding Ashalchinskoye and Mordovo-Karmalyinskoye bituminous deposits. In recent years, one of the experimental sites is the Lower-Karmalinsky bitumen deposit.

Upheaval is included in the group of similar syn-sedimentary morphostructure having a common spatial orientation. All the structural ridges are located within the western slope of the South Tatar arch, which is a monocline, stepping in steps plunging down to the Meleckess depression. According to one of the hypotheses, sedimentation-accumulative uplifts are bodies of sand bars elongated along the coastline of the Ufa Paleo Sea.
Currently, for development of the Lower-Karmalinsky bitumen deposit, steam assisted gravity drainage technology (SAGD) is being tested [3,4]. In the productive sandstone layer two horizontal wells are drilled one above the other. In the productive sandstone layer two horizontal wells are drilled one above the other. To the upper injection well is supplied water steam with a temperature of about +180°C, which heats the layer of bituminous sandstone. Condensing water enriches by hydrocarbons and enters the producing underlying well. Thus, between the two wells, a constant circulation of the oil-water fluid is created. Over time, the heat chamber increases in size, reaching 10.0-15 m. According to the simulation, the heat-affected zone can extend over distances of 25–30 m from the injection well.

The superheated water vapor injection into the bitumen deposit will drastically change the hydrogeological conditions of the reservoir, which can lead to changes of filtration-capacity properties of sandstone at developing. Under the influence of temperature, a wide variety of chemical reactions can be activated, contributing to the dissolution and subsequent deposition of mineral phases within the sand layer. Given this, in the proposed article, thermodynamic modeling of possible hydrochemical processes was carried out with an assessment of their effect on the bituminous reservoir being developed.

2. Object
Lower-Karmalinsky bituminous deposit tectonically is confined to the western slope of the South Tatar arch. Bituminous deposit belongs to the layer-uplifted deposit type. The bitumen-saturated rocks are sandstones of the Sheshminsky horizon of the Ufa low Permian tier (Piss) with an average thickness of about 26 m [2]. The reservoir is confined to the Lower-Karmalinsky brachial anticlinal structure, which stretch in the northeast direction. Its length is about 13 km, width - 2-3 km, height - up to 45 m.

In thermodynamic modeling, the data of the mineral composition of sandstones and the chemical composition of interstitial waters in the bitumen reservoir are used. As shown by optical studies, the bitumen-saturated reservoir is represented by greywacke sandstones [5,6], which are composed of the Ural magmatic complexes destruction products. In them, the debris components are represented by rounded fragments of mafics effusive rocks (55-60%), subrounded metamorphic and siliceous rocks (20-25%), subrounded quartz grains (15%), angular fragments of plagioclase and microcline (5%), and rare scales of muscovite and chlorite. Clastic fragments of minerals and rocks are cemented by clay-calcite cement, which constituting 10-30% of the rock. In the productive part of the bitumen deposits there is a cement of two types: pore-filling and argillaceous lump cement. In the most bituminous part of the sandstone pack, organic-mineral cement accounts for 10-35% of the rock. The organic components are represented by medium and heavy oil, as well as fragments of syngenetic organics of flora [7]; the mineral components are calcite and analcime. The sandstone reservoir porosity is not constant, varies from 10 to 30% [6].

The bituminous reservoir of the Lower-Karmalinsky field is coinciding with low yield aquifer and locally with water bearing stratum terrigenous complex of the Sheshminsky horizon of the Ufimian stage. Water-bearing rocks are porous sandstones and siltstones with a thickness of 4 to 29 m. The underground waters of the Ufimian sediments are pressure water, piezometric levels are set above the top of aquifer layer. The magnitude of the head flow above the top of the reservoir - from 50 to 60 m. Piezometric levels in wells are often set at absolute elevations from 75 to 80 m. Well water output (discharge) varies from 1.4 to 150 m³ per day. The recharge of the Sheshminsky horizon is carried out by infiltration from above and ascending filtration from below. Recharge of groundwater into the bitumen deposit occurs through cracks or tectonically weakened zones. The main direction of underground water flow is westerly direction towards to the Sheshma River valley. In the cross-section of the Lower-Karmalinsky bitumen deposit there are several aquifers, which are practically unrelated. The groundwater of deposit is sodium hydrocarbonate waters with TDS (Total dissolved solids) of 1.2-5.7 g/L, containing a significant amount of hydrogen sulfide [7]. Waters of the underlying sandstones and edge waters are sulphate-calcium-magnesium and hydrocarbonate-calcium type with TDS up to 1.0 g/L.

3. Results and Discussion
According chemical analysis data of bitumen deposit groundwater’s, which planned for development, hydrocarbonate ions are predominate in them, sulphate ion and chlorite ion are in small amount. From
cations, in accordance with the hydrochemical type, sodium ions prevails (Table 1). Potassium, calcium and magnesium ions are present in insignificant amounts. TDS of the formation water varies from 1.5 to 1.9 g/L, pH corresponds to weak acid medium with the temperature +8°C.

Table 1. The chemical composition of groundwater Lower-Karmalinsky bitumen deposit.

| Sample | The content of major elements, mg/L | mg/L | pH  |
|--------|-------------------------------------|------|-----|
|        | Ca²⁺                               | K⁺  | HCO₃⁻ | SO₄²⁻ | Cl⁻  |
| 1      | 12.82                               | 16.84 | 953.20 | 9.68  | 470.21 |
| 2      | 7.27                                | 16.27 | 1097.95 | 8.17  | 620.34 |
| 3      | 8.51                                | 24.45 | 1082.19 | 9.70  | 608.70 |
| 4      | 6.31                                | 20.09 | 922.78  | 9.18  | 557.79 |
| 5      | 9.23                                | 22.47 | 855.29  | 13.88 | 411.15 |

Given the temperature difference between stratal and injected waters is necessary to consider how increasing temperature in the bituminous reservoir will effect on the changes of groundwater chemical composition and their interaction with matrix minerals. Analysis of bituminous sandstone mineral composition showed that the most unstable phase will be calcite cement. Therefore, in this work we carried out a thermodynamic simulation of calcite interaction process with waters having different temperatures. Since the initial process water injected into the layer of bitumen-saturated sandstone has a temperature of +180°C, all calculations were carried out in the temperature range of 25-200°C. To calculate the temperature dependence of the Gibbs energy change, we used the carbonate equilibrium equation:

\[ CaCO_3 + H_2O + CO_2 = Ca^{2+} + 2HCO_3^- \]  \( (1) \)

The calculation was made according to the formula:

\[ \Delta rG(T) = \Delta rG^o(T) + R^*T^*\lg k \]  \( (2) \)

where \( R \) is the universal gas constant (8.3143 J * deg⁻¹ * mol⁻¹);

\( T \) – the absolute temperature;

\( k \) – the equilibrium constant of the reaction (1):

\[ k = \frac{a_{Ca^{2+}} \times a_{HCO_3^-}^2}{a_{CO_2}} \]

in which \( a \) – the activity of the reaction components (1).

The calculation of \( \Delta G^o(T) \) was made according to formulas 2.19-2.23 from [8] using the corresponding thermodynamic constants. The calculation was done for the two types of water: 1) stratal water, containing 8.83 mg/L of Ca²⁺ ions and 533.64 mg/L of HCO₃⁻ ions; 2) river water injected to well and containing 100.00 mg/L Ca²⁺ ions and 375.00 mg/L HCO₃⁻ ions. The results of the calculations are presented in the table 2.

For clarity of the process, using obtained data the plots were drawn. Figure 1 shows the dependence of the Gibbs energy change of equation (1) depending on the temperature of stratal water and heated river water injected to well. Analysis of calculations and graphs shows the following. In the heating stratal groundwater of bitumen reservoir the carbonate equilibrium (\( \Delta rG(T) = 0 \)) is established at temperatures of about +120°C. Calcite dissolution of cement occurs below this temperature; above, on the contrary, calcite precipitates. In the injected hot river water into the reservoir, carbonate equilibrium is established at a temperature of +90°C. Calcite dissolves below this temperature and precipitates above.
A question may arise whether calcite will dissolve simply by the action of water without the participation of carbon dioxide by the reaction:

$$\text{CaCO}_3 + \text{H}_2\text{O} = \text{Ca}^{2+} + \text{HCO}_3^- + \text{OH}^-$$  \hspace{1cm} (3)

since the initial components of this reaction are common for the system described by the carbonate equilibrium equation of reaction (1). We calculated the amounts of the Gibbs energy change $\Delta rG(T)$ and amount of the logarithm of the equilibrium constant $\lg k^\circ$ of reaction (3) for temperatures of 25–200°C. The results are shown in the table 3 and figure 1.

**Table 2.** Change of thermodynamic parameters $[\Delta fG^\circ(T)]$ components, logarithm of equilibrium constant ($\lg k^\circ$) and Gibbs energies $[\Delta G^\circ(T)$ and $\Delta G(T)]$ of reaction (1) at different temperatures for stratal and river waters.

| $T$, °C | Thermodynamic parameters of the reaction component, ($\Delta fG^\circ(T)$) | $\Delta rG^\circ(T)$, kJ/mol | $\lg k^\circ$ | $\Delta G(T)$, kJ/mol |
|--------|---------------------------------------------------------------|-----------------|----------|------------------|
| 25     | \begin{align*} \text{CaCO}_3 & = -1128.9 \quad \text{H}_2\text{O} = -237.1 \quad \text{CO}_2 = -394.4 \quad \text{Ca}^{2+} = -552.8 \quad \text{HCO}_3^- = -586.86 \end{align*} | 33.83 | -5.9  | -12.27 | -8.0 |
| 50     | \begin{align*} \text{CaCO}_3 & = -1122.3 \quad \text{H}_2\text{O} = -233.1 \quad \text{CO}_2 = -394.4 \quad \text{Ca}^{2+} = -553.6 \quad \text{HCO}_3^- = -578.09 \end{align*} | 39.97 | -6.5  | -10.00 | -5.4 |
| 100    | \begin{align*} \text{CaCO}_3 & = -1109.1 \quad \text{H}_2\text{O} = -224.9 \quad \text{CO}_2 = -394.6 \quad \text{Ca}^{2+} = -555.3 \quad \text{HCO}_3^- = -559.82 \end{align*} | 53.63 | -7.5  | -4.07 | +1.3 |
| 150    | \begin{align*} \text{CaCO}_3 & = -1096.1 \quad \text{H}_2\text{O} = -216.8 \quad \text{CO}_2 = -394.7 \quad \text{Ca}^{2+} = -557.3 \quad \text{HCO}_3^- = -540.61 \end{align*} | 69.07 | -8.5  | +3.64 | +9.7 |
| 200    | \begin{align*} \text{CaCO}_3 & = -1083.1 \quad \text{H}_2\text{O} = -208.6 \quad \text{CO}_2 = -394.8 \quad \text{Ca}^{2+} = -559.1 \quad \text{HCO}_3^- = -52.30 \end{align*} | 86.81 | -9.6  | +13.65 | +20.4 |

**Figure 1.** Synchronous thermal analysis data of the Middle Volga region oil shale deposit. The solid line is the differential scanning calorimetry (DSC) curve; the dotted line is the mass loss curve (TG).
These results show that the equilibrium constant of the reaction (3) is a million times less likely in comparison with reaction (1) and therefore it can be ignored.

4. Conclusions
Given the above, we can draw the following conclusions:

1. Depending on the mineral composition of water in the reservoir, when stationary conditions of develop are reached, it is necessary to maintain a temperature in the range from +90 to +120°C. In this case, a decrease in the bitumen viscosity will not be accompanied by processes of the "dissolution-precipitation" of calcites.

2. If it is necessary to improve the filtration-capacity properties of the reservoir, it is possible at the initial stages to maintain the temperature in the thermal chamber at the level of +70-90°C. This will lead to partial dissolution of calcite cement in sandstones.

3. To improve the technological characteristics of the reservoir layer and increase the recoverability of bitumen, it is recommended to inject hot water into the strata with low TDS and less mineralization.

Acknowledgments
This study was performed in the context of the Russian Government Program of Competitive Growth of Kazan Federal University.

References:
[1] E.A. Korolev, S.A. Usmanov, D.S. Nikolaev and R.R. Gabdelvaliyeva, “Effect of lithological heterogeneity of bitumen sandstones on SAGD reservoir development”, IOP Conference Series Earth and Environmental Science, vol. 155, art. #012019, 2018.
[2] E.A. Korolev, A.I. Bakhtin, A.A. Eskin and R.R. Hanipova, "Diagenetic changes of sandstone reservoir of Ashchalchinskoye bitumen deposit", Neftyanoe Khozyaystvo – Oil Industry, vol. 10, pp. 26-28, 2016.
[3] R.S. Khisanov, V.G. Bazarevskaya, T.I. Tarasova, A.A. Kostina, R.R. Abusalimova and S.A. Panina, “Classification of geologic cross-section types of Sheshminskian P1ss2 sand sequence”, Neftyanoe Khozyaystvo – Oil Industry, vol. 6, pp. 27-29, 2017.
[4] E.A. Korolev, M.G. Khramchenkov, E.M. Khramchenkov, A.A. Eskin, R.R. Gabdelvaliyeva and A.N. Garaeva, “Modeling of the suffusion cavities development in bitumen saturated sandstones of Ashchalchinskoye deposit under SAGD technology application”, Neftyanoe Khozyaystvo – Oil Industry, vol. 1, pp. 55-57, 2018.
[5] A.I. Mullakaev, R.R. Khasanov and B.M. Galiullin, “Mineralogy of sandstones and localization of oil matter in productive horizons of high-viscosity oil in permian deposits of the Volga-Ural region (Russia)”, 17th International Multidisciplinary Scientific GeoConference, vol. 17(11), pp. 353-358, 2017.
[6] R.R. Khasanov and A.I. Mullakaev, “Paleogeographic factors of the formation of Permian reservoir rocks of bitumen deposits in the east of the Russian plate (Russia)”, 16th International Multidisciplinary Scientific GeoConference, vol. 1(1), pp. 469-474, 2016.
[7] A.I. Mullakaev, R.R. Khasanov, O.R. Badrutdinov, N.M. Khasanova and N.M. Nizamutdinov, “Features of bitumen-containing sandstones of the Volga-Ural oil and gas province according to
Electron paramagnetic resonance and Gamma spectrometry data”, 17th International Multidisciplinary Scientific GeoConference, vol. 17(11), pp. 133-139, 2017.

[8] M. Borisov, Yu. Shvarov, Thermodynamics of geochemical processes (Moscow: MSU Publishing House), p 256, 1992.