Changes in the composition and properties of Ashalchinskoie bitumen-saturated sandstones when exposed to water vapor

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Abstract. Ashalchinskoie bitumen deposit is an experimental platform for testing technology of high-viscosity oil extraction from reservoir rocks. Last time for enhanced of oil recovery in reservoir used pressurization a water vapor with a temperature of ~ 180 °C (SAGD technology). However, what happens in sandstone reservoir is little known. We did a study of the effects of water vapor on the structural components of bitumen saturated sandstone. In paper were studied the rock samples at base condition and after one week exposure by water vapour. The thermal analysis showed that steaming helps to removes light and middle oil fractions with a boiling point up to 360 °C from oil saturated sandstones. Content of heavy oil fractions virtually unchanged. Studying the composition of water extractions of samples showed that the process of aquathermolysis of oil is accompanied by a lowering of the pH of the pore solution from 7.4 to 6.5 and rise content in several times of mobile cations \(\text{Ca}^{2+}\), \(\text{Mg}^{2+}\) and \(\text{HCO}_3^-\), \(\text{SO}_4^{2-}\) anions. Follows from this that the thermal steam effect by bitumen saturated sandstones leads to partial oxidation of hydrocarbons with to form a carbon dioxide. The source of sulfate ions were oxidized pyrite aggregates. Due to the increasing acidity of condensed water, which fills the pore space of samples, pore fluid becomes aggressive to calcite and dolomite cement of bitumen saturated sandstones. As a result of the dissolution of carbonate cement the pore fluid enriched by calcium and magnesium cations. Clearly, that the process is accompanied by reduction of contact strength between fragments of minerals and rocks. Resulting part of compounds is separated from the outer side of samples and falls to bottom of water vapor container. Decreasing the amount of calcite and dolomite anions in samples in a steam-treated influence is confirmed by X-Ray analysis. X-Ray analysis data of study adscititious component of rocks showed that when influenced of water vapor to bitumen saturated sandstones there are the processes of transformation of clay minerals. Mixed-illite-montmorillonite phase is primarily exposed to changes. In this case we fix initial stage of the destruction of polycrystalline particles mixed-mineral. Reducing the size of clay minerals particles along the normal to the layers (\(L_{001}\)) is the result from lower energy costs of delamination and disintegration the crystallites along this direction, in comparison with others. Thus, using of SAGD technology at exploitation of Ashalchinskoie bitumen saturated reservoir will be followed by acidification of the pore fluid, activation processes of dissolution calcite cement and transformation of mixed-layers clays minerals.
1. Introduction

Ashalchinsky bitumen field is one of the experimental objects for testing and optimization of high-viscosity oil extraction technologies located in the territory of the Republic of Tatarstan [1]. In the tectonic, the field is located on the western side of the Southern Tatar arch [2] (fig. 1). The productive strata are localized in the sandstones of the Sheshminsksy horizon of the Ufimian of the Lower Permian system [3]. The cap rocks are the "lingual" clays of the Baytugan horizon of the Kazanian of the Middle Permian system (fig. 2). Bituminous sandstone layers are characterized by variable reservoir properties and heterogeneous hydrocarbon saturation. The highest values of the capacitance-filtration parameters and the residual oil saturation are noted in the arched parts of the low-amplitude brachiancinal structures, the smallest ones in the saddles between them. Within the Ashalchinsky field, the deposits of high-viscosity oil are located at relatively shallow depths from the Earth's surface, from 80 to 200 m [5, 7]. It is believed that they formed as a result of the ascending migration of water-oil fluids from the underlying oil-saturated succession localized in Carboniferous successions [4, 6].

Figure 1. Object setting on schematic on tectonic map.
Legend: 1 – regional fractured zone; 2 – structural boundary; 3 – fractured zone; 4 – arch structure; 5 – name of structural elements (KKD – Kamsko-Kinelsky depression; NTA – North-Tatar arch; STA – South-Tatar arch; MD – Melekesskaya
Ashalchinskoye bitumen deposit is an experimental platform for testing technology of high-viscosity oil extraction from reservoir rocks. Last time for enhanced oil recovery in reservoir used pressurization a water vapor with a temperature of ~ 180 °C and pressure from 0,4-0,55 to 2,5-4,0 MPa (SAGD technology) [10]. However, what happens in sandstone reservoir is little known.

The SAGD technology has proven itself in the development of bituminous sandstones in Canada. The similar method of hydrocarbon extraction was applied on the Ashalchinskoye bitumen field. In the producing formation sandstone zone with thickness of 15-25 m were drilled two horizontal wells, located one above the other. In the upper intake well is supplied water vapor with a temperature of ~ 180 °C, which heats the bituminous sandstone bed. Condensing water is enriched by hydrocarbons and enters to the lower producing well. Thus, between the two wells going the circulation of the water-oil fluid. The formation of intensive circulation zone within a local area can lead to illuviation not only hydrocarbons from sand reservoirs but also their mineral components. If it poorly consolidated sandstones, then it can lead to problems in their development. Based on this concept the modeling of the effect of water vapor on the structural components of the bituminous sandstone of the Ashalchinskoye deposit was carried out.
2. Methodology

To assess the given fuel type adequacy for thermal energy production it is necessary to know its thermal characteristics and blend composition. The mentioned combined are to determine the combustible shale effectiveness as a fuel resource. In consideration of this the main research methods were X-ray, thermal and SEM analyses.

X-ray phase analysis. The X-ray phase analysis was performed on the diffractometer D2 Phaser (Bruker, Germany) used for measuring the powder products in the Bragg-Brentano geometry, with the use of monochromatic CuKα-radiation (λ = 1.54178 Å), in the step-scan mode. Measuring and recording modes: X-ray tube voltage-30 kV, current-30 mA. Scanning step-0.02°. Speed-1 deg/min. The range of scanning angles in the Bragg-Brentano geometry 3-40°. The standard powder compositions were used.

The thermal analysis was performed on the device STA 449 Jupiter F3 to determine the calorific value and phase transitions of the combustible shale structural components. The burning ranged from 30 to 1000 °C, the heating step – 10 deg. / min. with constant air blowing.

3. Results and Discussions

Lithological studies of terrigenous bitumen-saturated rocks are showed that the sandstone layer in both the dense and expanded bitumen-saturated part is characterized by a homogeneous composition of the allotgenic component. The prevalent are fain-grained fragments of siliceous and effusive rocks (~ 70%), in lesser quantities there are subangularity grains of quartz (~ 15%), angular grains of albite (~ 7%) and microcline (~ 3%), chlorite flakes (~ 3%), Rare rounded fragments of carbonate rocks (~ 2%).

Optical-microscopic data and sieve analysis of the sandstones fractional composition showed predomination of 0.1-0.25 mm size grains. Grains of siltstone and clay size are in a subordinate amount. At the same time, there is a tendency to reduce the content of siltstone component in the productive part of the sandstone pack in comparison with similar unchanged sandstones. The fragments are cemented by argillo-calcareous cement. In dense sandstones, the share of cement is 15-35%, in bituminous-saturated - 3-12% as shown in Table 1.

In intervals of bitumen-saturated sandstones are presence higher porosity and uniform saturation by oil hydrocarbons. The increase of the void space volume was due to the partial leaching of calcite from sandstone cement which substantially reduced the carbonate content of the rocks. Obviously, the first stage of the fluid impact was associated with the advent of aggressive solutions in the sandstone bed which dissolved the calcite cement and thus increased their filtration-capacitive properties. Aggressiveness of solutions to carbonates was probably due to the high content of carbon acid in them. The source of gas was the oxidizing oil deposits of Carboniferous deposits.

| Rock type          | Fraction content, % | Carbonate content, % | porosity, % |
|--------------------|---------------------|----------------------|-------------|
|                    | 0.5-0.25 | 0.1-0.05 | 0.05-0.01 | >0.01 |          |             |             |
| Dense sandstone,   |          |          |          |       |          |             |             |
| unchanged          | 0.14     | 61.43    | 18.43    | 14.07  | 5.93     | 15.66       | 6.16        |
|                    | 2.91     | 66.69    | 17.68    | 8.92   | 3.80     | 28.36       | 4.98        |
|                    | 0.0      | 61.32    | 18.82    | 10.62  | 9.24     | 33.39       | 3.44        |
|                    | 0.26     | 65.92    | 18.63    | 10.91  | 4.28     | 33.96       | 3.16        |
|                    | 0.46     | 64.55    | 18.91    | 13.97  | 2.11     | 35.45       | 2.31        |
X-Ray analysis data of study adscititious component of rocks showed that when influenced of water vapor to bitumen saturated sandstones there are the processes of transformation of clay minerals. Mixed-illite-montmorillonite phase is primarily exposed to changes. The diffraction data showed as the duration of the water vapor processing on sample are changing profile of basal diagnostic reflections from flat grid [001] \(d_{001} = 14.32 \text{ Å}\). This is showed in reduction of peak reflection intensity, its widening and asymmetry towards small angles. The decrease of the peak intensity and its widening are the result of reducing the size of the crystallites in the polycrystalline structure of the mixed-phase. In this case we fix initial stage of the destruction of polycrystalline particles mixed-mineral. Reducing the size of clay minerals particles along the normal to the layers (L001) is the result from lower energy costs of delamination and disintegration the crystallites along this direction, in comparison with others.

It was found that water vapor helps to bitumen viscosity reducer and partially hydrocarbons removal from sandstone pores. Intermediate oil fractions with a boiling point temperature up to 360 °C were completely washed out and amount of residual heavy fractions with a boiling point temperature above 400 °C decreased from 6.0 to 4.0%. X-ray analysis of the samples showed that content of calcite and clay minerals (illite-montmorillonite and chlorite) in bituminous sandstones after treatment with water vapor decreases [7]. Removal from the rock of the main cementing components leads to changes of sandstones physico-mechanical properties. After 50 hours of water-vapor treatment their density decreases from 2.06 to 1.8 g/cm³, unconfined compressive strength from 2.75 to 1.23 MPa, bending strength from 0.11 to 0.05 MPa, bond value from 0.45 to 0.21 MPa. It leads to increases the effective porosity from 10.7 to 18.2%. After 100 hours of water treatment, sandstones are dissolved and becoming sand. Granulometric analysis of sand showed amount reduction of elastic component, clay and silt fractions in composition. The rock became more uniformly, fine-grained.

Experimental work was performed to evaluate the effect of water vapor on the mechanical properties of bituminous sandstones. From the test core of the bituminous sandstone layer, cubes and cylinders were cut out, which were placed in a water bath.

At certain time intervals, the samples were tested for uniaxial compression (Rcomp.) and tension (Rst.). The obtained results presented in Table 2. They showed that the duration of the action of water vapor on bitumen-containing rocks leads to a progressive decrease in their strength characteristics. A similar tendency is due to a progressive decrease of the binding force (C) in the rocks due to the leaching of calcite cement and the elution of the hydrocarbon substance.

| Measurement parameters | Time of water vapor action on bituminous sandstones, hours |
|------------------------|----------------------------------------------------------|
|                        | 0             | 50             | 100            | 200            |
|                        | Poorly consolidated bituminous sandstone                 |
| R_{\text{comp.}}, MPa  | 2.75          | 1.25           |                |                |
| R_{\text{st.}}, MPa    | 0.11          | 0.05           |                | break          |
| C, MPa                 | 0.45          | 0.21           |                |                |

Table 2. Mechanical properties of Ashalchinskoye deposit sandstones
Strong cemented bituminous sandstone

|      | R_{\text{comp}}, \text{MPa} | R_{\text{st}}, \text{MPa} | C, \text{MPa} |
|------|-----------------------------|-----------------------------|--------------|
|      | 36.00                       | 1.44                        | 5.94         |
|      | 22.50                       | 0.90                        | 3.71         |
|      | 16.50                       | 0.66                        | 2.72         |
|      | 15.75                       | 0.63                        | 2.61         |

Research data show that the effect of water vapor on rocks can lead to a significant drop in the strength characteristics of sand collectors in the hydrocarbon recovery process (fig.3).

Estimation of the suffosive cavity size, as well as the time of its formation, according to Boek E.S. [8] is carried out taking into account the physical filtration rate $q_0$ of the fluid in the pores of each rock type, which characterizes the degree of cementation of the rock. The limiting cavity size $r_\infty$ can be calculated from the relation:

$$r_\infty = \frac{Q}{2\pi q_0 m_\infty T}$$

where $Q$ – production well rate; $T$ – linear dimension of exposed by drilling area; $m_\infty$ – maximum achievable value of the suffusion cavity porosity; $T$ – length of the exposed section by horizontal well. The time dynamics of the suffosive cavity formation can be obtained from the relation:

$$m = \frac{q}{q_0} \left[ 1 - \left( 1 - m_0 \frac{q_0}{q} \right) e^{-(q_0 \alpha t)} \right]$$

where $q$ - filtration rate; $m_0$ – initial value of porosity; $\alpha$ – erosion rate of the soil.

Choosing typical values of $q_0$ for different degree of cementation of rocks, we obtain the corresponding values of $r_\infty$.

Figure 4 shows plots of formed suffosion zone size from the degree of rocks binding force for sections of two horizontal wells of 200 and 400 m in length, and a flow rate of 20 and 34 tons per day, respectively. It can be seen from the graphs that when the cement is weakly cemented, the size of the cavity generatrix can reach considerable values.
Figure 4. The curves of the dependence of the formed suffusion cavity size in the bitumen deposit from the degree of rocks cementation. Legend: f1 - flow rate 20 m / day, length of the section 200 m; f2 - flow rate 20 m / day, the length of the section is 400 m; f3 - flow rate 34 m / day, length of the section 200 m; f4 - flow rate 34 m / day, the length of the site is 400 m.

4. Conclusions

Thus, the simulation showed that the process of bituminous sandstones development of the Ashalchinskoye field using the SAGD-technology will be accompanied by loosening of the rock structure and the suffusive removal of mineral particles by a filtration stream into producing wells. To theoretically substantiate of mineral particles removal possibility from the sand layer was calculated rock stability coefficient using the formula for calculated:

$$K = \frac{2\varepsilon H g \rho_r - P_{BH}}{\sigma_{CH}}$$

where $K$ – dimensionless coefficient; $H$ – depth of productive strata; $\varepsilon$ – coefficient of rock lateral thrust; $g$ – acceleration of gravity; $\rho_r$ – rock density; $P_{BH}$ – bottom-hole pressure; $\sigma_{CH}$ – rock compressive strength. Substituting the values corresponding to these quantities, we obtain the variation of $K$ from 15 to 53. It is believed that at $K = 1$ the rocks are in an equilibrium state, for $K > 1$ - the rocks are in a stressed state.

When most of the calcite cement was removed from polymictic sandstones, the effects of aggressive solutions began to be exposed to the surfaces of allotigic grains, primarily the weathered fragments of effusive rocks consisting of albite. The fragile, corroded surface acquired by the wreckage during transportation greatly contributed to the activation of hydrolysis processes on them. According to research [9], the feldspars hydrolysis is accompanied by ion-exchange reactions between $H^+$ and $Na^+$, as a result of which sodium ions leave for solution, and on the plagioclases surface the gibbsite-hydrogibbsite layer is formed. Apparently, something similar happened on the surface of fragments of effusive rocks. Before the formation of kaolinite, the process did not reach, which probably contributed to the arrival of water-oil fluids.

Thus, the result of the SAGD-development will be the destruction of the bottom-hole area, the flow of sand into production wells and as a consequence, the colmatage and underground equipment wear.
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