Physical Modeling of Oil Displacement in the Multifunctional Surfactant-based Chemical Composition

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Abstract. The paper presents the test results of a new multifunctional chemical composition based on surfactants in the process of displacement of heavy high-viscosity oil. Physical modeling of the oil displacement process was carried out in a laboratory setup which allows modeling heterogeneity of the oil-saturated formation. As a result of experiments it was found that the use of a multifunctional chemical oil-displacing composition based on a surfactant leads not only to a change in the filtration flows within the heterogeneous reservoir model but also to an increase in the oil displacement coefficient.

1. Introduction
The main method of developing oil fields in Russia is water flooding. About 95% of the oil is produced by this method. Currently, the major fields in Russia is on the late stage of development and the water cut of products exceeds 80%. New fields are characterized by low permeability, increased oil viscosity and complex geological structure, therefore their reserves are classified as difficult to recover. The part of hard-to-recover oil reserves in Russia is constantly growing and currently exceeds 60% (including high-viscosity oils - 13%, low-permeability reservoirs - 36%) [1-3].

The extraction of the resources requires new approaches and methods from developers optimized for specific deposits and conditions. For the effective development of hard-to-recover oil reserves, including Arctic oil fields, it is necessary to apply the scientifically based oil production technologies adapted to northern conditions and to develop new chemical reagents for the implementation of technologies [4-6].

An important direction in the search for ways to increase the oil recovery of heavy oil deposits is the development of new physicochemical technologies based on the addition of various types of chemical reagents into the reservoir, including those based on surface-active substances (SAS) [7-11].

In order to increase the oil recovery of high-viscosity oil deposits the Institute of Petroleum Chemistry of the SB RAS has developed a multifunctional chemical oil-displacing composition based on surfactants, aluminum and ammonium salts, an inorganic acid adduct, a coordinating solvent and urea (MFC). The composition has low hardening temperature, compatible with mineralized formation waters, and provides an adjustable viscosity over a wide temperature range, from 20 to 220°C, for achievement an optimal ratio of oil formation viscosities and the displacing working agent. It leads to an increase in the coverage factor of the formations.
The paper presents the results of laboratory tests of the effectiveness of the use of MFC for the displacement of highly viscous oil from carbonate source rock.

2. Materials and methods
Filtration tests of MFC were carried out on a setup for studying filtration characteristics (KATAKON LLC, Russia) in relation to the conditions of the Perm-Carbon deposit of the Usinsky field. The installation consists of two columns with a volume of 125 cm³ (core holders) filled with disintegrated core material. The different values of gas permeability in columns allow modeling heterogeneity of the formation. To prepare a heterogeneous reservoir model for experiments the column was sequentially saturated with a reservoir water of the Usinsky field with a mineralization of 62.1-74.7 g/l and degassed oil from the Usinsky field (heat-stabilized oil with the addition of 30% kerosene).

The effectiveness of the oil displacing composition was studied in the process of displacing residual oil with water.

Filtration studies of the effect of MFC on the process of oil displacement were carried out as follows. First, the oil was displaced by water to a complete water cut of the products from both columns at a given temperature. Every 5-15 minutes the temperature, pressure at the inlet and outlet of the columns, volumes of displaced oil and water from each column were measured. According to the obtained data, the pressure gradient grad P (atm/m), the filtration rate V (m/day), the fluid mobility k/μ (μm²/(MPa·s)), and the oil displacement coefficient Kᵥ (%) were calculated. After the oil was displaced by water, a strip of the oil-displacing composition was pumped simultaneously into both columns, pushed on a predetermined distance with water and thermostated for a certain time. Then the water pump was continued. Measurement of the above parameters — temperature, inlet and outlet pressures, volumes of displaced oil and water from each column — was carried out continuously every 5-15 minutes. In addition, the pH of the liquid at the outlet of the columns and the concentration of the urea included in the composition were determined. According to the data obtained, the pressure gradient, filtration rate, fluid mobility, and the absolute coefficient of oil displacement by composition and water were calculated.

3. Results and Discussion
For filtration tests and estimation of oil displacement ability four models of a heterogeneous reservoir were prepared (Table 1). The gas permeability of the columns in the heterogeneous reservoir model was in the range 0.250–3.120 μm². The relative permeability of the columns within the model ranged from 1.7:1 to 3.5:1.

Figure 1 shows the effect of injection of MFC on the filtration characteristics and oil displacement coefficient of a heterogeneous reservoir model of a Perm-Carbon deposit of the Usinsky field prepared from disintegrated core material.

Through the water-oil-saturated model of an inhomogeneous reservoir of core material in the “reservoir-well” direction, the reservoir water model of the Usinsky field was filtered with an injection rate of 1 cm³/min at 23°C. In this case the pressure gradient between the inlet and outlet of the model was 1.05 MPa/m. The initial oil saturation of the columns was 64.43 - 82.55%.

As a result of filtering the formation water model, oil displacement was observed, mainly from a more permeable column. The oil displacement coefficient for the first and second columns during the pumping of 4.2 pore volumes of the formation water model was 36.5 and 11.4%, respectively.

| Model | Gas permeability [μm²] | Pore volume [cm³] | Initial oil saturation [%] |
|-------|-----------------------|------------------|---------------------------|
|       | 1 column 2 column 1 column 2 column 1 column 2 column |                  |                          |
| 1     | 3.120 0.894 45.60 42.40 76.75 82.55 |                  |                          |
| 2     | 2.849 1.091 49.67 43.93 64.43 68.29 |                  |                          |
| 3     | 0.439 0.250 46.04 39.73 73.85 70.48 |                  |                          |
| 4     | 1.900 0.600 45.30 38.40 70.64 67.71 |                  |                          |
A strip of MFC in the volume of 0.5 pore volume was pumped in the well-formation direction and pushed through a predetermined distance with water. The 56% of the pump composition entered the first column, and 44% -the second column.

Figure 1. The effect of injection of a multifunctional chemical oil-displacing composition based on a surfactant on the filtration characteristics and oil displacement coefficient. The initial gas permeability of the first and second columns was 3.120 and 0.894 μm².

The model had withstood 12 hours before water was pumped in the direction of "reservoir - well". The fluid mobility in the columns decreased significantly, the pressure gradient increased to an average of 5 MPa/m when filtering through the model at a temperature of 23 °C. At the same time, an increase in the oil displacement coefficient from the first and second columns was observed 3.4 and 6.5%, respectively. After that the temperature was raised to 90°C and model stood for 2 hours before water pump continuation. The fluid mobility and filtration rate in the columns increased. An increase in temperature to 90°C with filtration of the formation water model led to additional 2% washing out of the oil from the second (less permeable) column.

At the same temperature, a second strip of the composition in the volume of 0.5 pore volume was pumped in the “well-formation” direction and pushed to the specified distance with water. The first and the second columns included 64% and 36% of the pumped composition, respectively. After thermostating at 90°C for 12 hours the filtration of the reservoir water model in the “reservoir - well” direction was resumed. The increase in oil displacement ratio was 0.7 and 2.0%, respectively for the first and second columns. Then the temperature was raised stepwise to 150 and 202°C with filtration of the reservoir water model through the heterogeneous reservoir model at each stage. The temperature increase resulted in an additional displacement of oil. The oil displacement coefficient after oil displacement by water and water with MFC was 42.18 and 25.86% for the first and second columns, respectively (average coefficient according to the model was 34.0%). The increase in oil displacement coefficient due to treatment with a multifunctional chemical composition based on a surfactant was 5.70% for the first column and 14.46% for the second column (10.8% on average).
The analysis of the components of MFC in the samples taken at the outlet of the heterogeneous reservoir model showed that the pH during the experiment decreases from 6.2 to 5.8 pH. After heating at 150 and 202° C and subsequent aging, urea hydrolysis resulted in pH shift to alkaline values of 8.9 pH. The concentration of urea in the samples of the selected water is 89.9 and 76.1% of the initial concentration in the first and second columns, respectively. It indicates a small degree of urea hydrolysis.

Filtration experiments 2, 3 and 4 were carried out in a similar way. Table 2 summarizes the results of the experiments.

| Model number | Column number | Gas permeability of the column [μm²] | The coefficient of oil displacement by water / water and composition [%] | The pumping volume of the composition (in V_pump of the sample), 1 and 2 pump | Maximum pressure drop during pumping of the composition [MPa/m] | An increase in the oil recovery coefficient [%] |
|--------------|---------------|--------------------------------------|-------------------------------------------------|-----------------------------------------|-----------------------------------------------|----------------------------------------|
| 1            | 1             | 3.120                                | 36.5 / 42.2                                      | 0.280                                    | 0.318                                          | 5.7                                    |
|              | 2             | 0.894                                | 11.4 / 25.9                                      | 0.221                                    | 0.183                                          | 6.75                                   | 14.5                                   |
| 2            | 1             | 2.849                                | 48.2 / 53.6                                      | 0.345                                    | 0.255                                          | 3.95                                   | 5.4                                    |
|              | 2             | 1.091                                | 1.8 / 36.8                                       | 0.155                                    | 0.245                                          | 3.95                                   | 35.0                                   |
| 3            | 1             | 0.439                                | 44.2 / 53.5                                      | 0.376                                    | 0.345                                          | 3.95                                   | 9.3                                    |
|              | 2             | 0.250                                | 43.0 / 66.5                                      | 0.169                                    | 0.245                                          | 3.95                                   | 23.5                                   |
| 4            | 1             | 1.900                                | 61.5 / 75.2                                      | 0.453                                    | 0.376                                          | 3.95                                   | 13.7                                   |
|              | 2             | 0.600                                | 21.0 / 64.4                                      | 0.047                                    | 0.230                                          | 3.95                                   | 43.4                                   |

All conducted experiments showed an equalization of filtration flows (fluid mobility in the columns) and an increase in oil displacement coefficients. An increase in oil displacement due to the use of the composition occurs both at low and at high temperatures. A pressure gradient of 3.95 - 8.97 atm/m was made for composition pumping, which can be reduced by increasing the pumping time.

An analysis of the components of MFC in water samples taken at the outlet of a heterogeneous reservoir model showed an increase in pH to a maximum of 8.9 pH. The pH are determined by the hydrolysis of urea and depend on the temperature of the experiment, at low temperatures the pH was in the range of 5.6 - 7.0 pH, at high temperatures - in the range of 8.5-8.9 pH, which was optimal for the most effective washing ability of surfactants. The urea concentration at the outlet of heterogeneous reservoir models depends on the temperature of the model: at temperatures below 90 °C partial hydrolysis of urea was observed, while at a temperature of 150-200 °C and a sufficient aging time the residual concentration of urea in the water samples was 46-56% from source one.

4. Conclusions

Thus, laboratory studies showed that the processing of a heterogeneous reservoir model saturated with highly viscous heavy oil with MFC resulted in the alinement of filtration flows and an increase of the oil displacement coefficients for individual columns from 5.4 to 43.4%. An increase in oil displacement due to the use of the composition occurred both at low and at high temperatures, which expands the scope of the possible use of the composition.
The industrial use of a multifunctional chemical oil-displacing composition based on surfactants, aluminum and ammonium salts, an inorganic acid adduct, a coordinating solvent and urea will increase the oil displacement coefficient and extend the cost-effective operation of fields at different stages of development. It helps to involve them in the development deposits with hard-to-recover hydrocarbon reserves, including Arctic high-viscosity oil deposits.

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