Low-Temperature Compositions with Two Gel-forming Components for Water Shut-off Purposes and Oil Recovery Increase

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Abstract. This paper presents the results of laboratory studies on the developed low-temperature nanostructured gel-forming compositions for water shut-off purposes. Kinetic and rheological tests of different gel-forming compositions have been carried out. The physical model is devised, and filtration characteristics of the compositions are studied. Ultimately, the efficiency of their application to limit water inflow and to increase the oil displacement coefficient is investigated.

1. Introduction

Watercut in the Russian oil industry as a whole is steadily increasing. Extraction of associated water requires large additional costs, which leads to an increase in the cost of oil as the watering of wells increases, forcing the premature transition of steam mechanized methods of production. Operation of a large number of wells, both oil and gas, is unprofitable due to the high watering of products and due to the economic inexpediency of further operation. The works aimed at studying this issue and developing gel-forming plugging compositions are particularly significant [1-3]. On the basis of a set of laboratory studies, The Institute of Petroleum Chemistry of the Siberian Branch of the Russian Academy of Sciences (Tomsk) previously created high-temperature (60-200 °C) nanostructured gel-forming compositions of MEGA and MEGA-PRO with two gel-forming components – polymeric and inorganic – with the improved rheological characteristics. Additionally, they developed technologies of their application for water shut-off purposes and for oil recovery increase under steam-heat and steam-cyclic impact [4]. The factor causing gelation is the thermal energy of formation or of the injected heat-transfer agent, without a crosslinking agent. The MEGA and MEGA-PRO compositions are developed on the basis of the “aluminum salt – cellulose ether – urea – water” system that consists of two thermotropic gelling systems: 1) “cellulose ether – urea – water”, thermotropic polymer solutions with low critical solution temperature (LCST), forming gels due to the reversible phase transition and 2) the inorganic system “aluminum salt – urea – water” forming gels due to the reaction of hydroxycondensation of aluminum ions. They form cohesively dispersed nanoscale structures of the “gel in gel” type.

The \textit{in-situ} formed gels of the reservoir inhibit the water or steam breakthrough from the injection into the producing wells, redistribute the filtration flow of reservoir fluids in the bed, which leads to stabilization or reduction in water production of the surrounding production or CSS wells and increases...
oil production. The first field tests of the technology with the use of the nanostructured gelling composition MEGA for water shut-off and enhanced oil recovery were successfully carried out in 2016-2017 at 9 producing wells of the Permo-Carboniferous deposit of the Usinskoye oilfield during CSS and steam flooding techniques. The volume of the injected composition was 80-120 m³ per well. After well treatment, a significant decrease in watering (by 12–40%) and a fold increase in oil flow rates were observed. The technology was recommended for industrial use.

MEGA-NT and MEGA-NT-PRO gel compositions have been developed to control filtration flows, to increase oil recovery and to sweep the efficiency of cooled reservoirs at 20-70 °C for low-temperature viscous oilfields. The difference between low-temperature gelling compositions and MEGA and MEGA-PRO compositions lies in the presence of a temperature regulating agent, which makes it possible to obtain aluminum hydroxide gels in formations with a lower formation temperature.

This paper presents the results of laboratory studies of MEGA-NT and MEGA-NT-PRO low-temperature gelling compositions.

2. Results and Discussion

The HAAKE Viscotester iQ rheometer (measuring system of coaxial cylinders CC25 DIN/Ti) was used as a rotary viscometry method to study gel kinetics. The solutions of MEGA-NT and MEGA-NT-PRO with different amount of thermoregulating agent (2, 3, 4 % wt.) were placed into the temperature-controlled cell of the viscometer and were (at continuous viscosity measurement) thermoregulated at different temperatures for a certain time. Viscosity measurements were made at shear rate 3 s⁻¹. The time of gel formation in solutions was determined by a sharp increase in viscosity due to the emergence of gel.

The mechanism of gel formation is different for solutions of the MEGA-NT and MEGA-NT-PRO in the temperature range above and below the LCST of the cellulose ether. When a solution of the composition is heated above the LCST of cellulose ether, in the temperature range of 60-70 °C, a polymer gel is first formed in the system due to a solution-gel phase transition, the polymer gel first forms, and the viscosity increases sharply. Following that, inside the polymer gel, the products of carbamide hydrolysis are initiated and an aluminum hydroxide gel is formed – that is, a gel-in-gel structure, which is accompanied by a further increase in viscosity.

When a solution of MEGA-NT and MEGA-NT-PRO is thermostated at a temperature below LCST of cellulose ether, a combined aluminum hydroxide gel is formed in the temperature range of 20-40 °C and additionally strengthened by reinforcing polymer molecules of cellulose ether and soluble carbamide-formaldehyde resin, which is accompanied by a sharp increase of viscosity.

As for the temperature range of 40-60 °C, both of these mechanisms of gel formation can be implemented depending on the concentration of the components of the composition and on the temperature regulating agent. In solutions of gelling compositions containing 3-4% wt. of temperature regulating agent, a combined gel is quickly formed. The solutions containing 2% wt. of temperature regulating agent a combined gel is formed after 6-7 hours. Moreover, a polymer gel of cellulose ether is formed more quickly in solutions of MEGA-NT-PRO compositions than in MEGA-NT solutions, but more slowly a combined gel.

The rheological properties of the solutions of the gelling compositions MEGA-NT and MEGA-NT-PRO before and after thermostating at different temperatures were studied by the method of rotational viscometry at a temperature of 20 °C at various shear rates from 1 to 1200 s⁻¹(Fig. 1 and 2). The gelling compositions before gelling are pseudoplastic fluids, the dependence of stress on shear rate is non-linear, and the viscosity depends on shear rates. The gels obtained from solutions of MEGA-NT and MEGA-NT-PRO compositions are viscous-plastic and have a spatial structure capable of resisting shear stress until its value exceeds the value of the critical (limiting) shear stress. Studies of the kinetics of gelation and the rheological properties of the solutions and gels of low-temperature gelling compositions MEGA-NT and MEGA-NT-PRO with two gelling components in the temperature range of 20 – 70 °C showed that obtained gel is the synergistic bonded nanoscale structure. Compared with one-component gels, this one has increased viscosity and elasticity.
Figure 1. Gelation kinetics at 23°C (a) and 70°C (b) in solutions of the composition MEGA-NT and MEGA-NT-PRO with different concentrations of temperature regulating agent measured by rotational viscometry.

Figure 2. Rheological flow curves (a, c) and viscosity (b, d) as a function of shear rate of solutions of MEGA-NT and MEGA-NT-PRO compositions.

To assess the oil recovery ability of MEGA-NT and MEGA-NT-PRO, the experiments were carried out at the facility to study the filtration characteristics of heterogeneous reservoir models both in natural operation mode and upon pumping hot water into the Permian-Carboniferous reservoir of the Usinskoye oilfield. Four heterogeneous reservoir models were prepared, consisting of two parallel columns filled with disintegrated core material and having different permeabilities. Figure 3 and Table 1 show the results of filtration tests of the MEGA-NT composition on a heterogeneous reservoir model.
In all the experiments, the presence of gelling compositions results in the leveling of filtration flows and in the additional washout of residual oil. The increase in oil displacement coefficients was in the range of 4.6–6.56% for a higher permeability column and 5.4–40.7 for a lower permeability column.

**Table 1.** Effect of gelling compositions MEGA-NT and MEGA-NT-PRO on oil recovery coefficients from non-uniform reservoir models

| Experience No. | Gas permeability, μm² | Oil displacement ratio, % | The increase of oil displacement ratio, % |
|---------------|-----------------------|---------------------------|------------------------------------------|
|               | column 1               | column 2                  | 1 column                                 | 2 column | 1 column | 2 column |
| 1             | 1.608                  | 0.808                     | 45.23                                    | 43.00    | 6.46     | 23.15    |
| 2             | 3.275                  | 1.293                     | 46.01                                    | 40.65    | 4.60     | 40.65    |
| 3             | 1.830                  | 0.892                     | 50.30                                    | 47.35    | 4.98     | 6.61     |
| 4             | 3.061                  | 1.087                     | 65.64                                    | 48.52    | 5.48     | 5.39     |

Thus, the experiments aimed at studying the filtration characteristics of a heterogeneous reservoir model (using low-temperature MEGA-NT and MEGA-NT-PRO nanostructured gelling compositions) have shown their high efficiency in blocking water breakthroughs and limiting water inflow at low temperatures, which contributes to an increase in oil recovery, which is especially significant for lower-permeability reservoir models.

**3. Conclusions**

MEGA-NT and MEGA-NT-PRO nanostructured gel-forming compositions with improved structural and mechanical properties have been developed. They lead to the appearance of nanostructured gels directly inside the formation. At the same time, there is a significant decrease in fluid mobility and the
levelling / redistribution of filtration flows, which leads to a selective limitation of water inflow (gels can withstand pressure gradients of 60-105 atm/m), to changes in the direction of filtration flows, a to a decrease in watercut, thus limiting the breakthroughts of the injected working agent into the producing wells. The expected result is intensification of oil production and increase of oil recovery factor. The MEGA-NT and MEGA-NT-Pro low-temperature compositions have improved structural and mechanical properties and can be applied for deflecting screens in oil formations, for redistribution of filtration flows, for increasing oil recovery and limiting water inflow, as well as for waterproofing of underground workings and hydraulic structures.

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