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New Thermotropic MEGA Systems with Two Gel-Forming Components to Restrict Water Inflow and Enhance Oil Recovery

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Abstract

The paper reports laboratory test results of the MEGA system developed at the Institute of Petroleum Chemistry of the Siberian Branch of the Russian Academy of Sciences. The composite was designed for enhanced oil recovery and restricted water inflow and had two gel-forming components, polymer and inorganic ones based on the aluminum salt – cellulose ether – carbamide – water system. The technology is intended to enhance oil recovery through increasing the coverage of the reservoir at flooding, steam-heat and cyclic steam stimulation and a restricted water flow in a wide temperature range (60–220 °C). As a consequence, the nanostructured "gel-in-gel" system with improved structural-mechanical properties is generated. Owing to gels formed in the reservoir water or steam breakthrough from injection wells into producing wells is restrained and filtration fluid flows in the oil reservoir are redistributed. That leads to a stabilized or reduced water cut of products of surrounding producing or steam-cycle wells and enhanced oil recovery.

Key words: enhanced oil recovery, water flow restriction, solutions, gels, kinetics, rheology, polymers, filtration

INTRODUCTION

A significant portion of oil fields in Russia merges into the late stage of development. The latter is characterised by increased water cut of wells as a result of the breakthrough of formation and pumped water through separate highly permeable channels, and also by decreased oil recovery. When using polymer or alkaline flooding methods premised on the alignment of the mobility of water and oil or the formation of water-insulating sediments that clog water-washed reservoir zones, bulks of reagents are required to draw through. Currently, preference is given to technologies using low-volume downloads (fringes). Herewith, water-insulating screens are developed in the bottom-hole zone of producing wells or deflecting screens in injection wells.

In order to enhance oil recovery and restrict water inflow for fields with hard-to-recover reserves, including high-viscosity oil deposits developed both without thermal impact and with the use of thermal method, thermotropic nanostructured gels with the complex hierarchical structure are used.

Works of the Institute of Petroleum Chemistry of the Siberian Branch of the Russian Academy of Sciences, implement the specified approach *via* making "intellectual" systems that are low-viscosity aqueous solutions under surface conditions and form coherently dispersed nanoscale "gel-in-gel" structures directly in the reservoir [1–5].

The objective of this research was to develop and laboratory test thermotropic MEGA systems with two gel-forming components, i.e. polymer and inorganic, for enhanced oil recovery and restricted water inflow.

EXPERIMENTAL

In order to restrict water inflow and enhance oil recovery of the Permo-Carboniferous reservoir in the Usinsk field upon thermal-stream and cyclic steam stimulation, a high-temperature (60–200 °C) nanostructured system was developed. The latter had improved rheological properties because of two gel-forming agents, i.e. polymer and inorganic.

In order to determine the optimum composition of the system, the kinetics of gel-forming and rheological properties thereof before and after gel formation were investigated. The research was performed by viscosimetry using a vibrational Reokinetica viscosimeter with a tuning-fork sensor and a rotational HAAKE Viscotester iQ Viscosimeter.

Analytical samples were prepared as follows: the solutions were placed in hermetically sealed steel cells, allowed to stand an air thermostat at temperatures of 90, 120, or 150 °C; removed and cooled to ambient temperature and then solution viscosity and pH were measured (at 20 °C). The acidity of the solutions was determined by the potentiometric technique using a glass electrode and a microprocessor laboratory pH meter manufactured by HANNA Instruments (Germany).

The research on filtration and oil-sweeping properties of the thermotropic MEGA system was carried out using a setup manufactured by Katakon LLC (Russia). The plant was comprised of two parallel columns with varying permeability; its capacity was 125 cm^3. In order to explore filtration properties, bulk models of the reservoir were used. The latter were prepared using disintegrated core material from the Usinsk field; fresh water or reservoir water model with mineralization 62.1–74.7 g/L; degassed oil (thermostabilised oil with the addition of 30 % kerosene) were used. The permeability of the models was found within 0.8 and 6.3 μm^2 and that of the parallel colons differed in 1.5–4 times. Temperature control time was selected considering gel formation kinetics (24 h), back-pressure of 2 MPa.

The oil-displacing ability of gel-forming systems was investigated as follows. The displacement of oil with water in both columns was initially carried out at 150 °C till complete products watering. Whereupon, gel-forming system plug was simultaneously pumped into both columns, promoted with water to a specified distance, and thermostated till gel formation followed by water injection. The temperature, the inlet and outlet pressures, and also amounts of displaced oil and water were recorded every 5–15 min. In addition, the pH of the liquid and carbamide concentration that was a part of the system were measured at the outlet of the columns. According to the data acquired, the pressure gradient, the filtration rate, the mobility of the liquids, and the absolute coefficient of displacement of oil with the composite and water were calculated.

RESULTS AND DISCUSSION

The authors have previously developed composites with one gel-forming component based on the ammonium salt – carbamide – water system [6]. When the temperature is higher than 70 °C, carbamide hydrolysis accompanied with a gradual increase in the solution pH to form ammonia and carbon dioxide proceeds therein. When the pH threshold value is reached, aluminum hydroxide gel is formed almost instantly at once in the whole bulk of the solution. Depending on modification, the gel is a pseudoplastic or viscoplastic substance with coagulation structure and distinct thixotropy. If the gel-forming process is carried out in the pore medium of the reservoir, the phase permeability of the rock may be reduced according to liquid. Gel-forming systems are translucent low-viscosity solutions that do not mix with oil and do not form stable emulsions with therein. The former do not cause the swelling of clays but are able dissolve carbonate minerals of the oil reservoir rock due to their acidity (depending on the concentration of aluminum salt at pH 3–4). They can be prepared using water of any mineralization.

Furthermore, the method of enhanced oil recovery of highly inhomogeneous seams at the expense of regulating filtration flows and increasing seam coverage by flooding with thermally reversible polymer gels was developed. The latter are based on a polymer system with lower critical dissolution temperature (LCDT). Gel formation under reservoir conditions is due to the thermal energy of the reservoir or injected heat carrier: when the temperature is increased, there is a phase transition, “solution – gel”. The process is reversible (the gel is deliquated with cooling) and may be multiply repeated.

The most promising polymers with LCDT are those based on cellulose ethers (CE). The viscosity of solutions of the cellulose ether – carbamide – water system in the 20–120 °C temperature range is of extreme nature: when heated, the viscosity is initially decreased and then increased. In other

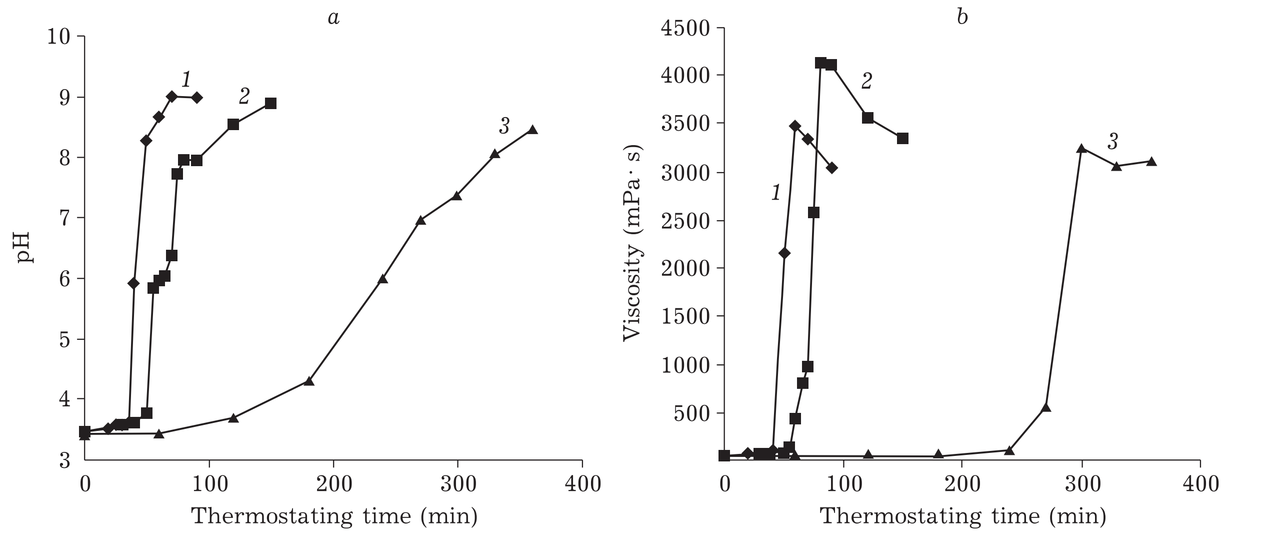

Fig. 1. Change in pH (*a*) and viscosity (*b*) of MEGA system solutions after thermostating at different temperatures, °C: 90 (*1*), 120 (*2*) and 150 (*3*).

words, the solution turns into a gel [7]. Gel-forming temperature and time may be regulated using organic and inorganic additives of electrolytes and nonelectrolytes. Their effect is additive. The gels are resistant at temperatures as high as 220 °C and may be used as efficient means to restrict water inflow, prevent gas breakthrough, and liquidate gas cones.

In order to restrict water inflow and enhance oil recovery of the Permo-Carboniferous reservoir in the Usinsk field upon thermal-stream and cyclic steam stimulation (CSS), there was developed the MEGA composite with two gel-forming components based on the aluminium salt – cellulose ether – carbamide – water system. The latter forms coherently dispersed “gel-in-gel” structures under reservoir conditions. When cellulose ether is heated above LCDT, a polymer gel is initially formed in the system at the expense of a reversible phase transition. Afterwards, aluminum hydroxide gel is generated inside of it according to the mechanism of hydrolytic polycondensation initiated by carbamide hydrolysis products. Owing to this, structural-mechanical properties of the gel, together with its viscosity and elasticity are increased.

Figure 1 reports research results on the kinetics of gel formation and the hydrogen indicator for solutions of the MEGA system. After thermostating at 90, 120, and 150 °C, the alkalinity of solutions is increased pH from 3.4–3.5 to 7.2–9.0 indicating hydrolysis of the carbamide that is a part of the system. There is also a drastic increase in viscosity from 44.2–65.8 to 3200–4300 mPa · s, which is indicated by gel formation.

Figure 2 gives research data for rheological properties of gel-forming systems. When shift rates are in the range between 0.1 and 500 s^{-1}, rheological flow curves were acquired. Furthermore, viscosity values of composite solutions were determined before and after gel formation at various thermostating temperatures. The solutions are pseudo-plastic liquids prior to their transition. The strain *vs* shifting rate relationship is of nonlinear nature and viscosity varies with shift rate.

The resulting gels have viscoplastic properties and are able towards elastic shape recovery after

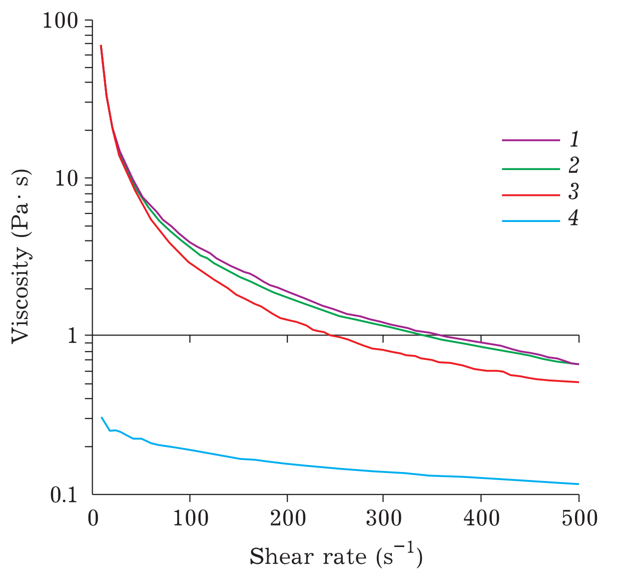

Fig. 2. Viscosity of solutions of MEGA systems *vs* shear rate before and after gel formation at various thermostating temperatures, °C: 90 (*1*), 120 (*2*), and 150 (*3*), without thermostating (*4*).

TABLE 1

Research results on filtration properties of the seam model of the Permo-Carboniferous reservoir in the Usinsk field when using gel-forming MEGA systems

Entry	Column gas permeability, μm^2		Ratio of perme-abilities	Ratio of mobilities		Oil recovery factor from column, %				Increase of oil displacement coefficient, %	
						with H_2O		with H_2O and system			
	1st	2nd		before pumping	after pumping	1st	2nd	1st	2nd	1st	2nd
1	1.5	0.8	2:1	3:1	1:1	29.8	32.2	47.5	54.1	17.7	21.9
2	1.8	0.9	2:1	1:1	30:1	33.6	28.8	55.6	41.7	20.0	12.9
3	1.4	3.4	1:2	1:36	1:3	2.7	47.2	41.9	53.2	39.2	6.0
4	2.0	1.4	2:1	1.5:1	1:1	50.7	58.1	79.8	73.6	29.1	15.5
5	6.3	1.5	4:1	4:1	1:4	34.3	20.1	44.5	28.1	10.2	8.0

stress relief. The spatial structure that remains under the effect of shift stress is typical for them. The former is preserved till its value is not higher than that of critical (threshold), after which there is structure decomposition. The ultimate shear stress for MEGA systems is found in the range between 433 and 590 Pa, which 1.6–2 times higher than for one inorganic component-based gels.

In order to physically model the process, restrictions of water inflow and enhanced oil recovery, five models of a non-homogenous seam were made. Each model consisted of two parallel columns with different permeabilities. The models were pre-saturated with a model of reservoir water and then with that of oil from Usinsk field. In such a manner, systems with the known initial oil saturations were produced.

Table 1 lists experimental results for the oil displacement process. A model of water was filtered through that of a seam at room temperature with a pumping rate of 1 cm^3/min. This process led to the displacement of oil, the amount of which was recorded. Filtering was continued until the complete water cut of the products. Oil displacement coefficients for each column were calculated according to the data acquired. A half of the pore volume of gel-forming nanostructured MEGA system was injected into a heterogeneous reservoir model and subjected to a steam cycle at 150 °C. Filtering was resumed after thermostating for 12 h. There was the redistribution (alignment) of filtration flows inside of the model of the homogeneous seam and a change in the ratio of liquid mobilities in the columns resulting from the treatment with the MEGA system. The pressure gradient required to break-through the gel screen was 6–14 MPa/m. There was also a substantial increment in oil displacement ratios amounting between 6.0 and 39.2 %.

CONCLUSION

The developed systems with improved structural-mechanical properties are promising to make deflector screens in oil reservoirs, the redistribution of filtration flows, enhanced oil recovery and restricted water inflow, and also to hydroisolate underground workings and waterworks.

As demonstrated by research on the kinetics of gel formation and rheological properties of solutions and gels, the resulting coherent dispersed nanoscale structure of gel-in-gel type has the enhanced viscosity and elasticity compared to gels with one gel-forming component. The limit stress of the shift of gels derived from solutions of nanostructured systems is between 433 and 590 Pa.

As shown by a set of experiments on non-homogeneous models of a seam under conditions that model reservoir ones, pumping the MEGA system leads to aligned filtration flows, enhanced formation coverage, and additional oil displacement. An increment in displacement ratio on average according to models is 9–23 %. The resulting gels may block water or vapour breakout in producing wells with a temperature of 60–220 °C withstanding pressure gradients of 6–14 MPa/m.

In 2016–2017, pilot tests of water shutoff and increased oil recovery technology were successfully carried out at the producing wells of the Permo-Carboniferous reservoir in the Usinsk field during CSS and in the area of thermal steam injection using the gel-forming nanostructured MEGA system.

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