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Experimental Study of Foam Gels for Regulating Filtration Flows of Fluids in Oil-Gas Condensate Reservoirs

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Abstract

The systems based on surfactants and inorganic reagents capable of generating stable foam gels *in situ* were investigated. Optimal ranges of component concentrations in the foam-gel forming systems intended to enhance oil recovery and coverage of oil and gas condensate deposits by the active systems of the development using water flooding, gas or steam injections were investigated.

Keywords: oil, gas, condensate, deposit, surfactants, foam gel, enhanced oil recovery, limitation of gas inflow

INTRODUCTION

The technologies of the production of oil and gas condensate, available today, are such that high-permeability reservoirs mainly are worked out in inhomogeneous complicatedly built collectors, and low-permeability layers (seams) either do not participate in the development or participate only partially. The increase in production from inhomogeneous deposits due to the development of low-permeability reservoirs is becoming an increasingly urgent task, as the largest deposits enter into the late development stage and the proportion of difficult-to-recover oil reserves is steadily growing. In this regard, new methods of the regulation, change of the structure of filtration flows of formation fluids, that will allow to increase the reservoir coverage involve the low-permeable reservoir zones in the development, exclude or reduce the coning and breakthroughs of water and gas (from a gas cap or bottom water) are necessary. The mobility of reservoir fluids is regulated with the help of foam systems [1–5]. One of the promising methods of the solution of this problem is the use of gel- and foam-gel forming systems.

A homogeneous aqueous solution containing a surfactant and inorganic gel-forming system based on carbamide and an aluminium salt is pumped into a reservoir. The propulsion of the solution into the stratum is implemented by nitrogen, carbon dioxide or hydrocarbon gas. Because of large differences in the viscosity of the gas and foaming solution when promoting (displacing) the solution in the porous medium of the formation the gas is dispersed by the mechanism of the capillary hydrodynamic instability with the formation of a gas emulsion or foam [1]. The gas can be pumped separately or together with a solution, compressor or ejector according to the scheme of the water–gas action or scheme of WAG scheme. Technology options without the gas injection are possible, for example, when foaming is effected by the gas released from oil at lowering the reservoir pressure below the saturation pressure or by carbon dioxide gas formed as a result of carbamide hydrolysis.

In the reservoir, due to its thermal energy or the energy of the injected heat carrier, carbamide hydrolyses gradually with the emission of carbon dioxide, due to which the additional and main foam formation in some variants is implemented. The increase of the alkalinity of the environment due to the carbamide hydrolysis leads to the hydrolytic polycondensation of monomeric aluminium ions and formation of aluminium hydroxide gel. The net-shaped structure of gelatinous gel of aluminium hydroxide formed in foam films prevents the expiry of the solution from the foam, shells of foam bubbles become more thick, the structural-mechanical strength of the foam is increased. Due to the stabilization of shells of foam bubbles by colloidal aluminium hydroxide dense foams and foam gels, stable in the presence of oil are formed. The time of gelation depends on the temperature and components ratio. In comparison with other technologies, the generation of the foam gel *in situ* reduces the consumption of commercial reagents to create deflecting screens in the reservoir and regulate filtration of gas-liquid flows.

Results of the experimental study of systems based on surfactants and inorganic reagents forming foam-gel *in situ* at high temperatures or thermal effect were considered in this work. Foam-gels allow implementing the physicochemical method of the regulations of filtration flows in productive reservoir of oil and gas condensate fields aimed at increasing the reservoir coverage by water-flooding to enhance oil recovery and limit the gas inflow.

EXPERIMENTAL

As the main gel-forming system for research, the inorganic thermotropic gel-forming GALKA® system developed at the Institute of Petroleum Chemistry, Siberian Branch of the RAS (IPC, SB RAS) has been selected. It is the system that is aluminium salt–carbamide–water, from which a gel is formed at a high temperature [6]. In order to study the foaming ability and the stability of foams from foam gel-forming system solutions with a various ratio of the non-ionic surfactant (NS) and anion-active surfactant (AS) or cation-active surfactants (CS) and components of the gelling system (aluminium chloride and carbamide) have been prepared. Commercially available surfactants were used: neonol AF 9-12 oxyetylated *iso*-nonylphenol on the ground of propylene trimmers with the degree of oxyethylation equal to 12 as NS; sulphonol that is sodium alkyl aryl sulphonate with the chain length of an alkyl radical C_{11}–C_{18} as AS; cetyltrimethylammonium bromide as CS. Solutions are prepared on the ground of water of a various mineralization, distilled and the model of cenomanian water of the composition (mass %): NaCl 1.370, $CaCl_2$ 0.130, $MgCl_2$ 0.039, $KHCO_3$ 0.027; pH 7.7, the density is 1009 kg/m^3. Experiments were carried out at the temperatures of 20, 30, 50, 70 and 90 °C.

The influence of the concentration and ratio of non-ionic and anion-active surfactants on the foaming ability and stability of foams, kinetics of gelation in systems forming foam-gels at a high reservoir temperature, physicochemical and rheological properties, filtration characteristics and oil-displacing ability of foam-gel forming systems and foam-gels were studied. The selection of optimal compositions in relation to conditions of fields of West Siberia with a high reservoir temperature (70–120 °C) and high gas factor, *viz.*, from 80 m^3/m^3 for oil and up to 1100 m^3/m^3 for gas-condensate deposits.

The density of solutions was determined by the pycnometer method, the viscosity by the method of vibrating viscosimetry using the vibrational viscosimeter "Rheokinetic" with a tuning fork sensor.

Experiments on the gas filtration through monolithic cylindrical samples from the sintered milled glass and natural core material at room temperature on a modified installation for the determination of the gas permeability of cores of the type GK-05 included in the set of the equipment AKM-"Kern". Samples dimensions: the length is 30–32 mm, diameter is 28 mm, and volume is 18–19 cm^3, V_{por} = 3–4 cm^3. The gas permeability of samples of sintered glass is equal to 10 μm^2. The installation allowed to inject portions of the systems into a gas flow filtered through the sample. In the filtering process of the gas with a constant flow the pressure drop across the sample was registered continuously automatically.

Experiments on the formation of foam-gels in the porous medium were conducted at the counterpressure of 6 atm and temperature of 130 °C in the installation for the study of the oil displacement with metal columns of the length of 30 cm and internal diameter of 2.0 cm, filled with silicagel ACKG. The gas permeability of columns is 10–20 μm^2, V_{por} = 66 cm^3. Columns under vacuum were filled with the formation water that was displaced by oil prior to the termination of the water displacement. Columns were placed in the oven and pressed at the pressure of 6–10 atm at room temperature for several hours, then thermostated at the temperature of 80 °C during several hours. After this oil displaced by the formation water to full water cut, *i. e.,* until the cessation of the oil displacement and by 30 cm^3 of a foam-gel forming system was injected into each column. Further, each column was injected with another 15 cm^3 of system water to remove the system from inlet pipes, the entrance of columns was blocked and thermostated at 130 °C at the counter pressure of 6 atm during the time, sufficient for the foam-gelation. In this case, some amount of water was left in the measuring tank at the outlet from the column with the purpose of visual monitoring the process of the gas-formation.

Oil-displacing properties of foam-gel forming systems were studied using the filtration installation UIPK-1 M under reservoir simulating conditions at 90 °C. The efficacy of the systems was studied in the process of the additional washing off process of residual oil and at the primary oil displacement. Besides, the oil displacement was conducted from two parallel columns with a different penetrability. The evaluation of the oil-displacing ability of foam-gel forming systems from the natural core material was conducted under conditions of the oil additional washing off and primary displacement on inhomogeneous models of the reservoir comprising two parallel columns with the common entrance and separate exit, the permeability in the limits from 0.064 to 0.880 μm^2. The permeability of the columns differed by a factor of 2.5–6 times.

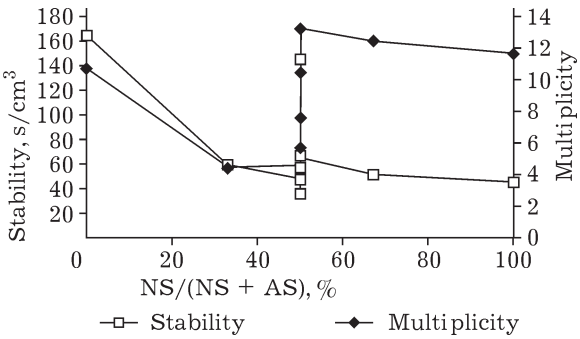

Fig. 1. Influence of the ratio of non-ionogenic and anion-active surfactants foam-gel forming solutions on the multiplicity and stability of foam at the temperature of 70 °C.

RESULTS AND DISCUSSION

Concentrations and ratios of surfactants

It has been found that at all temperatures the multiplicity and stability of foams increases with the increase of absolute concentrations of surfactants by more than 0.5 % and proportions of anion-active surfactants in a mixture with non-ionogenic surfactants. The multiplicity of foams was in the limits of 4–9 (the average value is equal to 8), and the stability of foams was in the limits of 36–165 s/cm^3 (the average value is 63 s/cm^3). Foams generated from systems with anion active surfactants possess the maximal stability. This is conditioned by its ability to form associates with aluminium ions in a foam film and thereby to increase the foam stability. The formation of associates is suppressed in the presence of non-ionogenic surfactants that form mixed micelles with anion-active surfactants. The sharp change of the stability and multiplicity of foams depending on the ratio of NS and AS in the solution (Fig. 1) indicates the difference of stabilization mechanisms towards anion-active and non-ionogenic surfactants.

It has been established that the interval of optimal concentration of surfactants for all temperatures is 1–25 mass % at the ratios of AS/NS, equal to 2 : 0, 2 : 1, 1 : 2, 1 : 1.

The ratio of surfactants affects poorly on the gel time. The influence of temperature on the gel time complies with Vant-Goff law: at increasing the temperature by each 10 °C the time gelation decreases in 3–3.5 times.

The density of the foams is in the range 0.09–0.18 g/cm^3, the density of froth gels is in

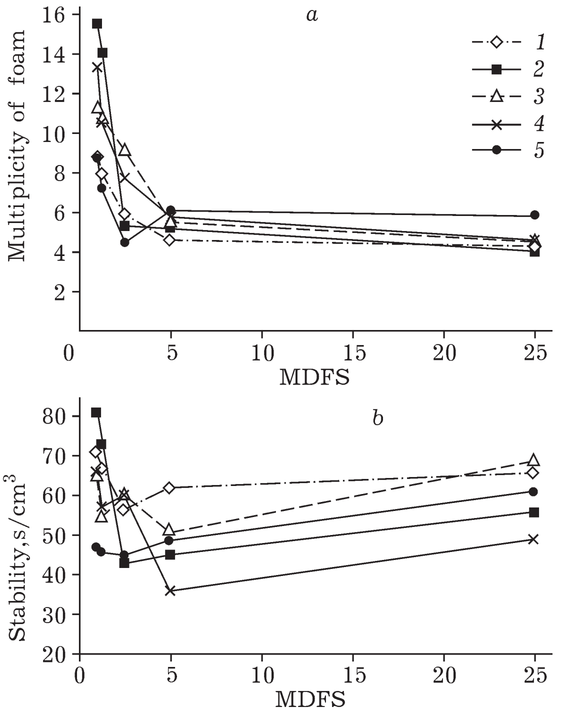

Fig. 2. Dependences of the multiplicity (*a*) and stability (*b*) of foam from the multiplicity of the dilution of a foam-gel forming solution (MDFGS) at different temperatures (°C): 20 (*1*), 30 (*2*), 50 (*3*), 70 (*4*), 90 (*5*).

the range 0.04–0.09 g/cm^3, what matches the values of multiplicity of foam and froth gels equal to 6–11 and 11–25, respectively. Viscosities of foams obtained from foam-gel forming solutions of a different composition are close in magnitude and vary in the limits of 31–76 mPa · s, moreover, the foam formed from the solution with the ratio of neuronal AF 9-12 and sulphonol 1 : 1 has the greatest viscosity. Values of viscosities of gels and foam-gels are close to each other in magnitude. The lowest viscosity is typical for the foam-gel, the initial solution of which contained neonol AF 9-12 only. The viscosity of foam-gels obtained from solution with the content of neuronal AF 9-12 and AS or KS in the ratios of 1 : 1.2 : 1 and 0 : 2 are close and they range in the limits of 750–3400 mPa · s.

The experiments aimed at establishing the effect of the dilution with cenomanian water of the initial foam-gel forming solution on the multiplicity and stability of the foam at different temperatures (Fig. 2). The foam-gel forming solution contains 4.1 % of anhydrous aluminum chloride, 15 % of urea, 2.5 % of neonol AF 9-12, 2.5 % of sulfonol and 75.9 % of cenomanian water. It has been discovered that when diluted in 5 times the ratio of the foam is reduced to 4 and it does not change at a dilution. The foam stability shows a similar dependence on dilution.

Foam-gel formation during the gas filtration through a porous medium

The experimental study on the gas filtration through monolithic cylindrical samples from sintered milled glass and natural core material (Figs. 3, 4) has been carried out.

Figure 3 demonstrates the character of the variation of the pressure drop in the process of the continuous of gas filtration with the constant flow rate and intermittent injection into the sample of portions of the solution of the gelling system first without surfactants-foaming agents and then a solution of foam-gel forming system. The portion volume was 1 cm^3; time of portion injection did not exceed 1 s. As can be seen, the initial plot (before the first injection) matches the gas filtration through an air dry the sample. After the second injection, the solution of gel-forming system filled completely the porous space of the sample. As a result, the phase permeability on gas decreased, what is reflected in a marked increase of a pressure drop. A small maximum in the curve indicates a gas breakthrough, after which the pressure drop is stabilized and subsequent injections

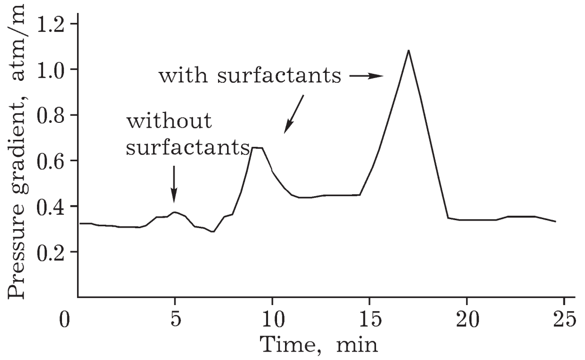

Fig. 3. Variation of the pressure drop on the sample in the process of the continuous gas filtration with a constant flow and periodical injection in a sample of a solution of gel-forming (without surfactants) and foam-gel forming (with surfactants) systems.

of the gelling solution no longer affect its value.

Injection of the foam-gel forming system the picture of gas filtering sharply changes. Thus, after the injection of each subsequent portion of this solution, a long asymmetrical peak of pressure is observed indicating the formation of the long-lived foam in the rim of the sample. Therefore, at injecting small water rims or gel-forming solution in the gas flow without a foaming agent the pressure drop conditioned by the filtration gas-water flow is much lower than the achieved drop at injecting a foam-gel forming solution.

The study of the generation of foam in the porous medium in the interval of the gas flow of 0.1–4 cm^3/min revealed the following patterns. Already at an insignificant gas flow (0.1 cm^3/min) foam is formed. The maximum of the filtration resistance of the foam to the gas flow does not depend on the gas flow, if the flow is lower 1 cm^3/min. The maintenance of certain foam content in the sample due to the continuous or periodic injection of the systems enables to achieve a significant, up to five-fold, increase of the filtration resistance for gas to the core sample.

Figure 4 demonstrates dependences of the pressure gradient in the sample at the filtration of the gas with a constant flow and periodic injection of portions of the foam-gel forming system. The injection of the regular portion was carried out at the moment of achieving the maximal pressure drop conditioned by the previous portion. Dependences obtained for two valued of the gas flow, 1.5 and 3.5 cm^3/min are given. First several portions of the system do not cause a marked foam generation, what speaks of the insufficient content of the foaming agent in the bulk of the system due to the foaming agent adsorption on the surface of pore channels. The foam generation starts only after the injection of 2–3 system portions, when the adsorption saturation of the surface of sample pores by a foaming agent is achieved.

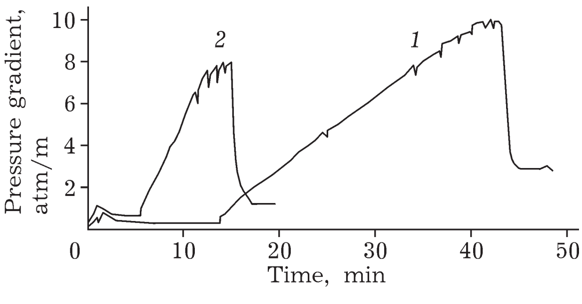

Fig. 4. Pressure gradient on the sample in the process of filtration of gas with the continuous flow and intermittent injection of the foam portions of the gel-forming composition. The gas flow (cm^3/min): 1.5 (*1*), 3.5 (*2*).

Similar patterns are observed when using foam-gel forming compositions containing cationic surfactants instead of anionic.

Foam-gel formation for levelling the injectivity profile

In the pilot study of the formation of foam-gels in the porous medium in the course of thermostating at the temperature of 130 °C, it has been established that since a certain moment, the gas barbotage through water in the measuring tank is observed, the level of the liquid increases and liquid samples from the measuring tank have the alkaline reaction of the environment. This indicates carbamide hydrolysis with the formation of ammonia and carbon dioxide.

At the beginning of the experiment the filtration of the formation water with the consumption of 4 cm^3/min is implemented at a very small pressure drop that cannot be registered by manometers included in the installation with the price of division of the scale of 1 atm. A significant filtration resistance was observed in 2 days for the column with the system containing cetyltrimethylammonium bromide and neonol AF 9-12, the maximal pressure drop on the column reached 30 atm, however, the gas evolution was not ceased. This indicates the *in situ* generation of the foam-gel. Upon reaching the maximal differential pressure, a breakthrough of water through the foam-gel, what was discovered by the sharp reduction differential, virtually to zero.

Oil-displacing properties of foam-gel forming systems

At the investigation of the oil-displacing ability of foam-gel forming systems under conditions of the additional washing off residual oil from the heterogeneous stratum model, it has been established that it is mainly included in the high permeable column (in the ratio of 15 : 1). As a result, the mobility of water when filtering through this column declines in 4.8 times, filtration flows redistribute, the residual oil is displaced from the low-permeability column. As a consequence, the coefficient of the oil displacement on the low-permeability column grew from 22.4 to 62.9 %, and as a whole, on the heterogeneous model of the reservoir from 51 to 68.2 %, *i. e.* by 17.2 %.

In the experiment on the primary displacement of oil the ratio of the injection volumes of the composition in columns with a different permeability was 2.8 : 1. This promoted the alignment of the profile of the pick-up of model: volumes of water pumped after the foam-gel formation of the composition were in the ratio of 1.25 : 1. As a result, high the displacement coefficients have been achieved: 71.2 % by the low permeable column and 79.9 % by the high permeable column and as a whole, 75.1 % by the model.

CONCLUSION

Physicochemical, rheological and oil-displacing properties of foam-gel forming systems based on the system aluminium salt–carbamide–surfactant–water have been studied. Optimal ranges of the concentration of components of foam-gel forming systems intended for the increase of the coverage of the heterogeneous reservoir by water-flooding, the alignment of the injectivity profile and enhance oil recovery of heterogeneous reservoir have been determined. The interval of optimal concentrations of surfactants is general for all temperatures and it is 1–25 mass % at the ratio of AC/NS, equal to 2 : 0, 2 : 1, 1 : 2, 1 : 1. 5-Fold dilution of the initial foam-gel forming solution with cenomanian water in 5 times causes reducing the multiplicity of the foam to the value of 4 that does not change at the further dilution.

Foam-gels are promising for the use in deposits of West Siberia, that are characterized by a high reservoir temperature (70–120 °C) and high heterogeneity. The physicochemical method using foam-gel enables to increase the oil recovery factor by 8–10 items, decrease the accumulated final water-oil factor at least in 1.3 times under conditions, when the permeability of high and low-permeability collectors differ in five times and more.

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