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INTRODUCTION

Physico-chemical control of filtration flows in the formation is considered to be a promising method to enhance oil recovery in oil fields developed by flooding. The methods increasing conformance by the injected fluid (water and gas) have been found to be the most effective in West Siberia. At a later stage of flooding physico-chemical control of filtration flows in heterogeneous reservoirs is carried out by selective isolation, i.e. blocking of well drained and highly permeable zones, causing the drowing of producing wells. It is convenient to employ gels with controlled generation time [1, 2].

A novel method has been developed to enhance oil recovery from highly heterogeneous formations. The method is used to control filtration flows and to increase conformance under flooding by thermoreversible polymer gels (TRPG). TRPG are prepared from polymer solutions with lower thermal critical solution point (LCSP). The formation heat energy causes gelation. Polymer solutions with LCSP are capable to gelation in situ: at low temperatures they are low viscous solutions, whereas at high temperatures they convert into gels. The process is reversible, i.e. at cooling gels dilute and become again low viscous solutions, while reheating causes gelation. The process can be repeated many times. One can vary temperature and time of gelation by organic and inorganic additives, taking into account the specific formation conditions, i.e. temperature and water mineralization.

By means of TRPG one can effectively reduce watercut, prevent gas breakthrough, eliminate gas cones etc. In 1996-1997 pilot tests of thermoreversible gels have been carried out to enhance oil recovery in oil fields of West Siberia. The technologies are economically effective and ecologically acceptable. The period of payback is about one year.

PHYSICO-CHEMICAL ASPECTS FOR GENERATION OF THERMOREVERSIBLE POLYMER GELS

Hydrodynamic and physico-chemical aspects of gelation in heterogeneous formations have been studied. Gel-forming systems have been developed. They have various gelation time - from some hours to some days in the temperature range from 40 to 100 °C. Aqueous polymer solutions with LCSP were used as gel-forming systems. Added were the components to control time and gelation temperature. These gel-forming systems were named METKA systems.

Bottom hole area of injected wells and oil formations of Jurassic and Cretaceous deposits of highly overflooded oil fields of West Siberia are usually cooled by the injected water. For Jurassic deposits, the initial temperature of which was 90-95 °C, at a later stage of field

development the temperature in injection wells decreased to 40-70 °C. Therefore selecting gel-forming systems we took real formation temperature into account.

The studies on gelation kinetics, TRPG rheological characteristics and on the effect of gels generated in situ at the formation temperature on filtration characteristics and displacement factor enable one to select suitable gel-forming systems to control filtration flows of the formation fluids, to limit water influx and to increase conformance under flooding with reference to the specific geological-physical conditions of West Siberia oil fields.

Gels are prepared from polymer solutions, whose curve of phase equilibrium liquid-liquid in the system polymer-water is characterized by lower critical solution point. At the temperatures below LCSP the system is homogeneous and if the temperatures are above LCSP it decomposes into two phases. The first phase is a highly diluted polymer solution and the second one - a concentrated solution. Because of high viscosity of the second phase the decomposition is retarded, the process is nonequilibrium. Microheterogeneous kinetically stable structure, i.e. thermoreversible polymer gel, arises, in which the concentrated phase serves as a dispersed medium for the phase diluted through a polymer.

The capability of system polymer with LCSP-water to form gels at the increased temperatures allows to use them for EOR technologies intended to increase conformance under flooding via selective isolation of the displaced highly permeable formation zones. Cellulose ethers (CE) are the most promising polymers with LCSP.

THE REGULATION OF TEMPERATURE AND TRPG GELATION TIME

Gelation in the system oil - reservoir rock - CE aqueous solution with LCSP has been studied. The dependence of solution viscosity in the range of 20-95 °C is of extremal character - at heating one can observe viscosity decrease from 40-80 mPa·s to 5-20 mPa·s, and then at further heating the viscosity increases up to 200-2000 mPa·s (Fig. 1). The solution converts into gel. The process is reversible. One can regulate gelation temperature (T_g) and time (t_g) in a rather wide range. The added salts of strong acids decrease t_g and T_g . T_g decrease linearly depends on electrolyte molality (Fig. 2). It is defined by anion nature in accord with lyotropic series and is practically independent on cation nature. 5% NaCl added to CE decreases T_g from 69 to 48 °C and 5% CaCl_2 - to 56 °C, respectively. Mineralized formation and injected waters in oil fields have the similar effect (Fig. 1). Alkali metal and ammonium rhodanides cause an opposite effect. Carbamide and thiourea additions, affecting hydrophobic interactions and hydrogen bonds, also increase time and temperature required for gelation of CE solutions, proportional to nonelectrolyte concentration (Fig. 3).

The introduction of T_g decreasing salts into CE solution causes strong oversaturation of the solution relative to phase equilibrium curve and thereby decreases t_g . Thus, adding 1% NaCl to CE solution at 50 °C one can observe the gelation in 12 hours; at 60 °C t_g is equal to 105 min, at 70 °C - 70 min, at 80 °C - 40 min and at 90 °C - 25 min, respectively. 10% NaCl addition causes gelation at 50-70 °C in 15 min, at 80 °C - in 10 min and at 90 °C - in 5 min, respectively. The addition of T_g increasing substances rises t_g . Thus, carbamide addition into CE solution increases t_g , which is linearly connected with carbamide concentration. Like electrolytes, carbamide is the most effective at lower temperatures, i.e. at 60-70 °C. At the elevated temperatures temporal differences of gelation smooth over (Fig. 4). At 60-90 °C one can observe correlation between t_g changes and T_g shift caused by electrolyte and nonelectrolyte additions. Knowing T_g one can preliminary determine gelation time at a given temperature.

Taking into account geological-physical conditions of oil fields, in particular, formation temperature, mineralization of the formation and injected waters, one can select gel-forming systems to regulate filtration flows and to increase watercut. For West Siberia oil fields proposed are METKA systems based on CE and additives regulating temperature and time of gelation.

FILTRATION AND OIL-DISPLACING PROPERTIES OF GEL-FORMING METKA SYSTEMS

Filtration characteristics and oil-displacing capacity of gel-forming METKA systems have been studied. The systems generate gel in situ at the formation temperatures of 40-90 °C under the conditions of Jurassic and Cretaceous deposits of West Siberia oil fields. The efficiency of gel-forming systems was studied at filtration through water-saturated models and in the process of residual oil displacement from a heterogeneous formation model. It consists of two parallel columns of different permeability.

The injection of METKA system was carried out simultaneously into both columns. The volume ratio injected into high- and lower permeable columns was in the range of 1.9-8; and in one of the experiments it was 28.8. It correlates with the initial gas permeability, equal to 3.8-5.7 and 20.4 and with the ratio of model permeability as to liquid, equal to 2.6-8.5 and 28.6. The slug value of METKA system in lower permeable columns was 0.009-0.129 of pore volumes, whereas in higher permeable column - 0.168-0.270.

After the injection of a gel-forming system and gelation in the simulated formation model the pressure rised and then in all the experiments one observed water break out through gel slug in a lower permeable column. As a result the pressure dropped and then it fixed at a definite level. The rearrangement of filtration flows occurred (Figs. 5 and 6). Liquid filtration proceeded mainly through a lower permeable column, whereas only a small part filtrated through a higher permeable column. The proportion of filtrated liquid volumes through columns changed by 10-200 times as compared to the initial one (before the injection of a gel-forming system). Liquid mobility in a high permeable model sharply decreased (Figs. 5 and 6). The rearrangement of filtration flows was accompanied with oil displacement mainly from low permeable columns (Fig. 5). The increase of oil displacement factor was 4.8-10%.

Thus, based on the study of filtration characteristics and oil displacing capacity of METKA systems, it has been determined, that the injection of gel-forming system's slug into a heterogeneous simulated formation model causes rearrangement of filtration flows. The mobility of liquid in a high permeable column sharply decreases, whereas in a lower permeable one it remains at the same level. The rearrangement of filtration flows is accompanied with residual oil displacement. The process is more intensive from a lower permeable column.

FIELD TESTS OF GEL-FORMING METKA SYSTEMS

In 1996-1997 pilot tests have been carried out in Pokachevskoye, Nivagalskoye, Pokamasovskoye and Las-Yeganskoye oil fields of JS Company "LUKoil-Langepasneftegaz" to enhance oil recovery from Jurassic and Cretaceous deposits of West Siberia. In 1996 gel-forming METKA systems were injected into 11 injection wells and in 1997 15 pilot areas were treated. METKA systems improve water injection profiles, decrease watercut and increase oil production of the producing wells, that are hydrodynamically connected with injection ones. Additional oil production is 1-3 thou tons per a well treated.

Standard oil equipment was used to prepare and to inject METKA systems. METKA systems have been found to be noncorrosive and technological for the conditions of West Siberia oil fields. The components are dissolved in water at 20-25 °C to give transparent solutions without odour and taste. Cooling of solution favours solubility increase. The best solubility is achieved at 0 - 10 °C. All reagents are large-tonnage commercial products. They are ecologically acceptable and easy to work under the conditions of oil fields.

The use of gel-forming METKA systems to regulate filtration flows of the formation fluids, to limit water influx and to increase conformance of flooded heterogeneous reservoirs in West Siberia oil fields has a payback within one year.

Gel-forming METKA systems are recommended to treat bottom holes and to affect the formation in a whole to enhance oil recovery by the injection of system slugs into injection wells. The size of gel-forming system's slug is determined taking into account geological-physical conditions and the stages of oil field development. It is possible to use gel-forming systems to isolate water influx in the producing wells.

CONCLUSION

- A novel method has been proposed for EOR of highly heterogeneous formations using thermoreversible polymer gels.
- Studied were rheological characteristics of cellulose ether solutions with lower thermal critical solution point, the effect of electrolytes and of nonelectrolytes on the temperature and kinetics of gelation. Gel-forming METKA systems have been developed with controlled temperature and time of gelation. They are effective for Jurassic and Cretaceous deposits of West Siberia.
- Filtration characteristics and oil-displacing capacity of METKA systems have been investigated. The injection of gel-forming solution's slug into a heterogeneous simulated formation model caused the rearrangement of filtration flows, which in its turn, was accompanied with residual oil displacement predominantly from lower permeable seams.
- The results of pilot tests carried out in West Siberia oil fields showed that the injection of METKA systems into the injection wells improves the injection profile, decreases watercut of the producing wells and thereby increases oil production. After the treatment of one well the additional oil recovery is an average of 1-3 thousand tons.
- Gel-forming METKA systems are effective to regulate filtration flows of the formation fluids, to limit water influx and to increase the formation conformance of flooded highly heterogeneous reservoirs in oil fields.

LITERATURE

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Fig.1. Rheological characteristics of aqueous solutions of cellulose ether versus temperature. 1, 2 - formation waters of Tuymazinskoye and Sovetskoye oil fields, 3, 4 - Senomanian and fresh water, respectively.

Fig.2. The effect of electrolytes on gelation temperature for aqueous solutions of cellulose ether: 1- fresh water, 2 - 1% CaCl_2 , 3-1% NaCl , 4 - 5 % CaCl_2 , 5 - 5 % NaCl , 6 - 10 % CaCl_2 , 7 - 10 % NaCl .

Fig. 3. The effect of carbamide on gelation temperature for cellulose ether dissolved in fresh (1) and Senomanian (2) waters.

Fig. 4. Gelation time for aqueous solutions of cellulose ether with different carbamide contents versus temperature.

Fig. 5. Rearrangement of filtration flows and additional oil displacement in a formation model after the injection of gel-forming METKA system.

The initial permeability of column 1 - $0.682 \mu\text{m}^2$ and of column 2 - $2.914 \mu\text{m}^2$.

Fig. 6. Rearrangement of filtration flows in a formation model after the injection of gel-forming METKA system.

The initial permeability of column 1 - $0.224 \mu\text{m}^2$ and of column 2 - $0.826 \mu\text{m}^2$.