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Experimental study and application of gels formed by nonionic polyacrylamide and phenolic resin for in-depth profile control

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ABSTRACT

A phenolic resin cross-linked nonionic polyacrylamide (NPAM) gel used for in-depth profile control was systematically analyzed. Long gelation time and strong gel strength of the gel system was obtained by adjusting NPAM or cross-linker concentration. An increase in temperature and salt concentration accelerated the gelation process and improved the gel strength. Although shearing brings a negative effect on gel performance, the gel system still had strong gel strength which could make it long-term stability in in-depth formation. Differential scanning calorimetry determined that this gel system should be used for oilfield application at temperatures below 143 °C. A compact three-dimensional network structure was formed in the bulk gel system and in porous media which contributed to long-term gel stability in the formation. Sand-pack flow experiments showed that the NPAM gel had a good plugging capacity and could selectively plug high permeability zones. By retention, adsorption, and bridging across the pore throats, the gel systems effectively reduced the permeability of porous media in high permeability zones and diverted fluid into low permeability zones, and thus improved the formation profile. Furthermore, this gel system for in-depth profile control treatment was successfully used in the Xinjiang oilfield of China which provided a reference for other similar high water cut oilfields for water control worldwide.

1. Introduction

Excessive water production is one of the most serious problems in mature oilfields. Water production not only limits the life of production wells but also causes several problems including corrosion, lift expense, separation, pumping, filtering, water reinjection, and underground and surface water pollution (Seright et al., 2003; Bedaiwi et al., 2009; Zhao et al., 2014; Muhammed et al., 2012; Bai et al., 2012). Therefore, reduction in water production becomes an increasingly important objective for mature oilfields. In-depth profile control technology is usually used to control water production. In-depth profile control technology involves injection of plugging agents from water wells into high permeability channels in the in-depth reservoir (Zhao et al., 2006; Moradi-Araghi, 2000; You and Zhao, 2007; Ju et al., 2008). When the plugging agents are properly placed, they can cause the injected fluid to flow through previously un-swept low permeability zones, thus improve the formation profile and drive out the remaining oil.

Recently successful applications of cross-linked polymer gels for in-depth profile control technology have emerged for their cost efficiency, controllable gelation time, and adjustable strength (Mohammad et al., 2007; Sengupta et al., 2012; Reddy et al., 2003; Al-Muntasheri et al., 2006). Different gel systems used for in-depth profile control technology depend on different reservoir conditions. Generally, the most commonly used gel systems are mainly composed of synthetic polymers or biopolymers and inorganic or organic cross-linkers. The polymers with carboxylate groups usually react with inorganic cross-linkers and form cross-links along the chain (Kurenkov et al., 2001). Chromium, aluminum, and zirconium are the most commonly used inorganic cross-linkers (Zolfaghari et al., 2006; Ranganathan et al., 1998; Dai et al., 2001; Zhang et al., 2014), and the resulting gels are suitable for lower temperature reservoirs (< 60 °C). But these gels take several hours to cross-link at high temperature reservoirs (> 60 °C), which further reduces the propagation of gelant solution into in-depth target formations. Moreover, these gels typically have lower thermal stability in high temperature reservoirs, resulting in over cross-linking or syneresis, and produce a failed in-depth profile control treatment. Organic cross-linking reactions involve the formation of covalent bonds between amide groups of the polymer and the cross-linker, which usually forms a good stable gel in high temperature reservoirs. Typical organic gels consisting of a polymer and phenolic resin cross-linker have been widely used for water profile control technology with reservoir temperatures

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above 60 °C. Previous studies have shown that anionic polymers and hydrophobic associative polymers are mainly used for the cross-linking reaction, and the cross-linking mechanism of these gel systems has also been described (Zhao 2010; You et al., 2010). However, the initial viscosity of these polymers is usually high which causes difficulties for the injecting process and flow in the porous media. Additionally, shearing degradation, uncontrolled gelation time, and uncertainty of gelling usually results in a failed profile control treatment. Fortunately, gels based on NPAM have been studied for profile control treatment in mature reservoirs (Zhang et al., 2013). The low viscosity before cross-linking and shearing resistance have potential applications for in-depth profile control technology in mature oilfields. However, no systematic study has been done for the gelation performance and microstructure of bulk gels under hydrated conditions and in porous media. So in this research, we focused on the gels based on NPAM for in-depth profile control technology. In addition, an oilfield test was also conducted to confirm that using phenolic resin cross-linked NPAM gel is an effective in-depth profile control technology for water production control. Through the laboratory experiments and oilfield test, we hope the work can further promote application for water production control in mature oilfields.

2. Materials and methods

2.1. Materials

Nonionic polyacrylamide (NPAM) and phenolic resin cross-linker were purchased from Yuguang Co. Ltd., China. The hydrolysis degree and average molecular weight of NPAM were 3.31% and 9,650,000 g/mol, respectively. The low salinity of brine (492.08 mg/L) was used in all experiments.

2.2. Preparation of gels

The solution before being gelled was a gelant solution which contained a NPAM solution and cross-linker. The preparation process was as follows. 1.0 g of NPAM polymer was added into 200 g of injection water and stirred to produce a 0.5% polymer solution. Then, the 0.5% NPAM solution was diluted to the required concentration (0.2%, 0.3%, and 0.4%) at room temperature. Sequentially, the phenolic resin cross-linker was slowly dropped into the NPAM solution and stirred to produce a uniform gelant solution. Finally, about 25 mL of gelation solution was injected into an ampoule through tygon tubing, and then the ampoule was sealed at the neck. The cross-linking reaction was initiated by heating the gelant solution in an oven.

2.3. Measurement and analysis

2.3.1. Determination of gelation time

To study the effect of various parameters on the gelation time of the NPAM gel, a gel strength code method was conducted to determine gelation time (Sydank and Argabright, 1987). The gel strength during development of gelation kinetics was expressed as an alphabetic code of A through I which is shown in Table 1. In the experiment, the ampoule was inverted at frequent intervals until the gel strength did not change, and the time was noted as the gelation time.

2.3.2. Determination of gel strength

The gel strength was determined by the breakthrough vacuum method (Zhao et al., 2013). Fig. 1 shows the experimental setup. The experimental procedure was as follows. The gel (25 mL in volume) was first put into a cuvette. Then a pipette was placed into the cuvette until the end of determination. Finally, the maximum pressure was recorded in the whole process which was noted as the gel strength. In the experiment, the breakthrough pressure of water (25 ml) was determined as a base line, and the water strength was 0.007 MPa. Each sample was measured three times to reduce experimental error.

Table 1
Gel strength code.

Gel strength code	Gel description
A	No detectable gel formed
B	Highly flowing gel
C	Flowing gel
D	Moderately flowing gel
E	Barely flowing gel
F	Highly deformable non-flowing gel
G	Moderately deformable non-flowing gel
H	Slightly deformable non-flowing gel
I	Rigid gel

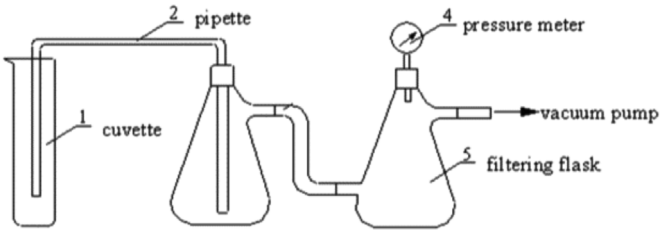

Fig. 1. The experimental setup to determine gel strength.

2.3.3. Microstructure of bulk gel

A Quanta 200 FEG environmental scanning electron microscope (ESEM, FEI Company Hillsboro, OR) was used to determine the microstructure of the bulk gel. A drop of bulk gel was removed from the ampoule and then directly placed on a covered ESEM grid. The temperature and accelerating voltage were initially set at 0 °C and 15 kV, respectively. The pressure was set from 313 Pa to 455 Pa while the working distance ranged from 5 mm to 10 mm.

2.3.4. Plugging capacity of the NPAM gel

Sand-pack flow experiments were used to determine the plugging capacity of the NPAM gel. Fig. 2 shows the experimental chart. A 0.3 PV (pore volume) of NPAM gelation solution was used during the flow experiments. The sand-packs were kept at 80 °C until the gel was formed. Then, water flooding was conducted until the pressure and produced fluid reached a stable condition. During the experimental process, water production and pressure were recorded to calculate water cut, plugging rate, and resistance factor (Zhao, 2006). These three parameters were used to characterize the plugging capacity of the NPAM gel. Sand-packs 45 cm in length and 2.5 cm in diameter were used in all experiments.

2.3.5. Flow behavior of bulk gel in porous media

A JSM-7600F scanning electronic microscope (SEM, JEOL, Ltd., Japan) was used to study the gel flow behavior in the porous media. 1.0 PV of gelant solution (0.3% NPAM +0.6% phenolic resin cross-linker) was initially injected into a core (Ø 25 mm × 80 mm). Then the core was placed in an oven and the cross-linking reaction was initiated at 80 °C for 5 days. Subsequently, a vacuum cup of liquid nitrogen was used to freeze the core for 2 h, and then the core was placed into a lyophilizer for 24 h with a vacuum pressure ranging from 7 Pa to 8 Pa. Finally, about 30–40 mm of core was cut away from the inlet and investigated by the SEM equipment.