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Experimental study of swelling and rheological behavior of preformed particle gel used in water shutoff treatment

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ABSTRACT

Production of water effluents in mature reservoirs subjected to water flooding face many difficulties that might, ultimately, lead to their abandonment. Gel shutoff treatment of such reservoirs using preformed particle gel (PPG) is a technique used to block fracture channels and to insulate highly permeable zones. The technique not only reduces water production but leads also to successful conformance control. The present study introduces a novel type of PPG with an extremely high swelling ratio. The PPG is made up of polyacrylamide and Aluminum nitrate nanohydrate, which acts like a superabsorbent to absorb water equivalent in weight to 1000–2000 times the dry weight of the gel. Tests were conducted in the present experiment to investigate the effects of polymer and crosslinker concentrations, temperature, salinity, and pH on the swelling of PPG. Results showed that increasing polymer and crosslinker concentrations as well as enhanced salinity led to declining PPG swelling ratio. While PPG swelling ratio was not considerable outside the pH range of 5–9, its rate within this range was relatively high. Moreover, PPG swelling ratio increased only slightly with increasing temperature by up to 100 °C, beyond which the 3D network structure of PPG collapsed. Rheological tests were performed to determine PPG strength in three samples selected based on least salt sensitivity factor values. In addition, the core flooding test was performed to evaluate the blocking efficiency and the performance of the three samples in reducing water production in sandpacks. The test results revealed that PPG reduced water effluents in the sandpack by 30%–65%.

1. Introduction

Oil production and extraction from hydrocarbone reservoirs typically decline after years of extraction and well operation. These mature reservoirs are subsequently subjected to water flooding to enhance their oil recovery, which causes excess water production through time. The situation becomes even more complicated due to the presence of underground conduits and fracture channels connected to aquifers that intensify the water effluent problem in oil reservoirs. Increased excess water effluent followed by reduced oil recovery poses economic limitations to reservoir survival (Elsharafi and Bai, 2012). In addition, the excess water effluent in oil reservoirs causes such additional problems as increased operation costs to separate water from oil, increased corrosion of machinery and equipment, environmental pollution, reduced well operating life, and ultimately well shut-in (Zhao et al., 2015; Alfarge et al., 2017; Lenji et al., 2018). Gel treatment is one of the most effective and practical techniques used to prevent and reduce excess water production in hydrocarbon reservoirs. This chemical technique, capable of plugging fractures and high permeability streaks, reduces excess water production to enhance oil sweep efficiency and, ultimately, achieve successful conformance control (Goudarzi et al., 2015). In this method, in-situ gels are injected into the reservoir to form a 3D gel network structure under the reservoir conditions (temperature, salinity, and pH) that will block water currents and reduce permeability (Seright, 1991; Sydansk and Moore, 1992). However, the method is plagued with such drawbacks as failure to control gelling time, gelation uncertainty due to shear degradation, gel dilution by formation water, and damages inflicted on low permeability un-swept oil zones (Abdulbaki et al., 2014; Sang et al., 2014; Zhao et al., 2018). In a more recent form of the technique, PPGs are synthesized using Surface facilities in order to overcome the defects associated with in-situ gel so that the 3D gel network forms outside the reservoir. The dried gel is

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then broken into desirable pieces and injected into target zones (Bai et al., 2007; Saghafi et al., 2016). The particles thus injected form a type of superabsorbent polymer that can swell by absorbing water several times its dry weight to stop or divert water in the fracture channels and void space conduits in high permeability zones, whereby water effluents are reduced and oil sweep efficiency is improved (Elsharafi and Bai, 2016).

Numerous studies have in recent years been conducted on PPG propagation mechanism and its performance in fracture channels and porous media focusing specifically on the effects of such parameters as particle size, salinity, and swelling on PPG propagation in such media (Seright, 1999; Bai et al., 2007; Bai and Zhang, 2011). Moreover, the effects of PPG composition (including monomer, crosslinker, and initiator concentrations) and environmental factors (including temperature, salinity, and pH) have been investigated on PPG strength and swelling ratio (Bai et al., 2007; Bai, 2010; Moghadam et al., 2012; Tongwa and Bai, 2014). PPG simulations and mathematical modeling have been also conducted to predict PPG performance and propagation in fracture channels and sandpacks. Resistance factor (RF) and residual resistance factor (RRF) in these models are typically expressed as functions of gel strength, gel concentration, salinity, and flow rate (Shi et al., 2011; Wang et al., 2013; Goudarzi et al., 2015; Alfarge et al., 2017; Chen et al., 2017). In most investigations, polymerization of acrylicamide free radical, acrylic acid, and N,N′-methylenebisacrylamide is used to synthesize PPG. In this process, N,N′-methylenebisacrylamide is used as the crosslinker and ammonium persulfate as the initiator (Bai et al., 2007; Zhang et al., 2015; Saghafi et al., 2016; Farasat et al., 2017). In some studies, use has also been made in the polymerization process of such commercial polymer superabsorbents as LiquiBlock 40K and Daqing (DQ) with the chemical composition of polyacrylic acid and polyacrylamide crosslinked with potassium salts (Bai and Zhang, 2011; Elsharafi and Bai, 2012, 2016).

The present study introduces a superabsorbent performed particle gel synthesized from polyacrylamide, used as the polymer, and Aluminum nitrate nanohydrate, used as the crosslinker. Moreover, the effects of polymer and crosslinker concentrations as well as temperature, salinity, and pH of the medium on the swelling ratio of the PPG used in water shutoff treatment are investigated. Finally, rheological tests are performed to determine the strength of the PPGs and the core flooding test is used to evaluate its performance in reducing water in sandpack.

2. Experimental

2.1. Materials

Sulfonated polyacrylamide (SNF, France) with an average molecular weight of 2000 kDaltons, a sulfonation degree of 25%, and a water content below 10 wt%; Aluminum nitrate nanohydrate (Sigma-Aldrich Co., Germany); sodium chloride, sodium hydroxide, and hydrochloric acid (all from Merck Co., Germany) were used without further purification. Deionized water was used in the synthesis of the superabsorbent polymer. Table 1 reports the composition of the formation water used in the core flooding test.

Table 1
Chemical composition of formation water.

Composition	Concentration (ppm)
Na^+/K^+	63024
Ca^{2+}	13600
Mg^{2+}	2673
Cl^-	127436
HCO_3^-	2440
SO_4^{2-}	500
Total	209673

2.2. Preparation of preformed particle gel (PPG)

Sulfonated polyacrylamide powder was initially dissolved in deionized water for 24 h to obtain a homogenized solution. The polymer solution thus obtained was then allowed to react with the crosslinker Aluminum nitrate nanohydrate and mixed thoroughly using a magnetic agitator for 10 min to obtain a gellant solution. The gellant was then transferred into sealed tubes and stored in an oven at 90 °C for 48 h. After the 3D gellant structure had been formed, the sample was placed again in an oven at 90 °C for 24 h to obtain a completely dried polymer gel. Pieces of the dried gel were finally broken to obtain the desired PPG.

2.3. Swelling measurement

Water absorption or swelling ratio of the PPG thus obtained was measured using the gravimetric method. Briefly, a known weight of the dry PPG was soaked in 500 ml of water for 24 h. After this time the residual water in the container was separated from the swollen PPG using a paper filter. The swollen PPG was then weighed and the swelling ratio was determined using the following eguation (Saghafi et al., 2016):

$$SR = \frac{m_s - m_d}{m_d} \quad (1)$$

where, m_d and m_s represent PPG dry and swollen weights, respectively.

Salt sensitivity factor was also determined in an electrolyte solution using the following equation (Aalaie et al., 2008):

$$f = 1 - \frac{SR_e}{SR} \quad (2)$$

where, SR and SR_e represent PPG swelling ratios in deionized water and in the electrolyte solution, respectively.

2.4. Kinetics of swelling

The dynamics of water sorption process was investigated based on known amounts of water imbibed by the PPG at various time periods. The swollen PPG was taken out at intervals for weight measurement. The simple power-law equation was used to determine the kinetics of the swelling process in the PPG network (Gharekhani et al., 2017):

$$\frac{M_t}{M_\infty} = kt^n \quad (3)$$

where, M_t and M_∞ are the cumulative amounts of water at time t and at equilibrium state, respectively; k is a geometric constant for a given system; and n is the diffiusional exponent representing the mechanism of swelling. Most published studies reported $n \leq 0.5$ for Fickian diffusion (Peppas et al., 2000; Ismail et al., 2013; Gharekhani et al., 2017). Fickian diffusion, refers to a situation where water penetration rate in the gels is less than the polymer chain relaxation rate. Therefore, $n = 0.5$ indicates a perfect Fickian process.

2.5. Microstructure characterization

Environmental scanning electron microscopy (ESEM, Quanta 200, FEI Co.) was used to observe PPG microstructures without damaging the network structure. Briefly, a piece of swollen PPG was placed on a covered ESEM grid. The pressure and temperature of the ESEM system were initially set to 130 Pa and 0 °C, respectively. Determinations were conducted at accelerating voltage of 25 kV, with a working distance of 5–10 mm.

2.6. Thermal stability measurement

PPG thermal stability was measured using a DSC 302 system