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Preformed particle gel propagation and dehydration through semi-transparent fractures and their effect on water flow

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ABSTRACT

Polymer gels have been widely applied to plug high permeability streaks or fractures, and to improve sweep efficiency of chase waterfloods. This work constructed semi-transparent fracture models to investigate gel propagation and dehydration behaviors using preformed particle gel (PPG) in open fractures. Roubidoux sandstone slabs were used in the models because they could better model the roughness of fractures and PPG dehydration in a real fracture system, which was rarely reported in earlier studies. Injection rate, fracture width, particle size, brine and gel concentration were taken into account to understand their effects on particle gel extrusion. Experimental results showed PPG propagated like a piston along a fracture when the fracture width was smaller than or similar to the particle size; and gravity will dominate the PPG movement when the fracture width was larger than the particle size. PPG dehydration decreased with the increasing gel injection rate, fracture width, and brine concentration used to prepare PPG. Higher PPG injection rates and lower injection rates for chase waterfloods are recommended to improve the sweep efficiency in the matrix. This study could provide an insight into the particular PPG gel treatment for conformance improvement.

1. Introduction

Excess water production is a major issue that leads to early well abandonment and unrecoverable hydrocarbon for mature oilfields. High permeability streaks, fractures, conduits, and fracture-like features are the main causes for undesirable water channeling and early water breakthrough during water flooding. Gel treatments have often been used to improve reservoir conformance and reduce water production in mature oilfields (Zitha and Darwish, 1999; Broseta et al., 1999; Zaitoun et al., 2007; Sang et al., 2014). These gel treatments depend heavily on the ability of the gels to extrude through the fractures (Seright and Liang, 1994; Seright and Lee, 1999; Brattekas et al., 2016). Therefore, it is important to understand the behavior of the gel extrusion through the fractures to optimize gel treatment design.

Extensive studies have been focused on gel transportation through fractures and channels using in-situ gel systems. Seright (2001, 2004; Seright and Lee, 1999) has investigated the extrusion of bulk gels through fractures and tubes. He studied the effects of fracture conductivity, tube diameter, and gel injection rates on gel extrusion behavior. Similar experiments were also conducted in University of Kansas to understand the propagation of bulk gels through fractures, tubing, and high-permeability sandpack and to determine how water injected into a gel can rupture that gel and form a flow path to conduct water (Ganguly et al., 2001; Al-Assi et al., 2009; McCool et al., 2009). Wilton and Asghari (2007) developed an acrylic fracture model and observed water penetration into HPAM-Cr (III) gel system which was dominated by one major channel. Since 1997, preformed particle gels (PPGs) systems have been developed to overcome some drawbacks inherent in an in-situ gelation system, such as lack of control over the gelation time, gelling uncertainty due to shear degradation, chromatographic fractionation, and dilution by formation water (Coste et al., 2000; Bai et al., 2007a, 2007b; 2013; Han et al., 2014). Some experimental results on PPG transportation through porous media were reported in the literature. Bai et al. (2007a; 2007b) studied swollen PPG transportation through porous media using sand pack and micromodels, and divided PPG movement into three patterns including pass, broken and pass, and plug. Challa (2010) developed a screen model to study the rheology behavior of PPG injection through various screen models, and revealed gel strength is a more controlling factor than the particle size of the swollen PPG for the particle injectivity. Imqam et al. (2015b) investigated PPG's injection and placement mechanisms through Super-K permeability cores, and examined the effect of sand permeability, PPG size, concentration and water salinity. Regarding the gel transportation through fractures, Zhang and Bai (2011) developed a

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transparent model with open fractures to visualize PPG propagation through fractures and to determine which factors affect particle gel injectivity significantly. Imqam et al. (2015a) conducted extensive experiments on the opening conduits, and examined the effect of the conduit inner diameter and the PPG strength on the ratio of the gel particle size to the opening diameter, injectivity index, resistance factor, and plugging efficiency. Imqam et al. (2016) also used five-foot tubes to mimic open fractures and built two-parallel-fracture models with different width ratios, and showed that the fraction of flow in the small fracture width depended on gel strength and fracture width ratio. However, their transparent models or conduit models was not permeable which ignored the leakoff of real fractured systems. Besides, the transparent model or conduit model may be also not the appropriate one to indicate the truth of the PPG propagation in fractures according to the study of Wang and Seright (2006). They found the roughness of the fracture is a vital factor for the propagation of gelant/gel/PPG. The smooth wall will contribute to an evident wall slip effect. And with the wall slip effect, the PPG can be easily moved with a small pressure gradient. Panthi and Mohanty (2017) developed fractured core models and revealed that the pH-insensitive polymeric particles could plug fractures in reservoir rocks and divert fluid (brine, toluene, or CO_2) to recovers oil from previously unswept matrix. However, the gel placement in the fracture could not be visually tracked.

On the other hand, leakage in the matrix rock of a real fracture system can significantly affect gel propagation and distribution in fractures due to the changes in gel concentration and strength caused by gel dehydration (Seright, 2001). During the process of filtration, the concentration of salt water will change, which will influence the process of PPGs dehydration. Ganguly et al. (2001) found that along with the filtration, the concentration of cross-linker stays in a stable value. In that case, the gelant can turn to be mature gel during the propagation in the fractures. For the same reason, in the proceeding of filtration, the concentration of salt can also maintain at a stable value which is higher than the concentration prepared the PPGs. And that attributes to a sustainable process of dehydration. Elshatafi and Bai (2015) built a static filtration test model and load pressure model and found that there is no swollen PPG particles with a range of millimeter to micron can penetrate through the porous media when the ratio of the particle size compared to the pore throat size is beyond 17.

In order to get the most closely to the real condition in the reservoir, a semi-transparent fracture model made of a plate of acrylic and one plate of sandstone was designed in this study to stimulate the process of propagation, and to investigate the swollen PPG propagation and dehydration process. This model consists of a single wing fracture system with a transparent wall for visual tracking. The rheological behaviors of PPG along with fluid leakoff properties in the fracture systems were monitored and the effects of various parameters such as injection rate and fracture width were evaluated. This study could provide vital suggestions for technical instructors to improve the effectiveness of PPG treatment and to save economic cost.

2. Experimental section

2.1. Materials

2.1.1. Preformed particle gels

The commercial superabsorbent polymer, LiquiBlock 40K Series (Emerging Technologies Inc., Greensboro, NC), was selected as the PPG sample for the experiments. Currently the millimeter or sub-millimeter sized PPGs are often applied in oilfields to reduce water flow through high permeability streaks/fractures. Table 1 lists some typical characteristics of the PPG used, and Fig. 1 shows the size distribution of the dry PPG particles, as determined by a sieving test (Bai, 2012). The dry PPG particles could absorb a large amount of water because of a hydrogen bond with the water molecules, although the concentration of sodium chloride affects its capacity to adsorb water. According to the previous study (Qiu et al., 2017), the water salinity for PPG field applications ranged from 1700 to 320,000 mg/L, and the median value was about 10,000–15,000 mg/L. In this study, the swollen PPG samples were prepared using three brine (sodium chloride) concentrations (0.25, 1, and 10 wt%) with gel swelling ratios of 98, 52, and 32, respectively. The particle concentration varied, depending on brine concentration. The PPG concentrations were calculated using the initial weight of the dry PPG, divided by the final weight of swollen PPG. Fully swollen PPGs, without excess (free) water, were used for all experiments.

Table 1
Typical characteristics of preformed particle gels.

Properties	Value
Absorption deionized water (g/g)	> 200
Apparent bulk density (g/l)	540
Moisture content (%)	5
pH value	5.5–6.0 (± 0.5; 1% gel in 0.9% NaCl)

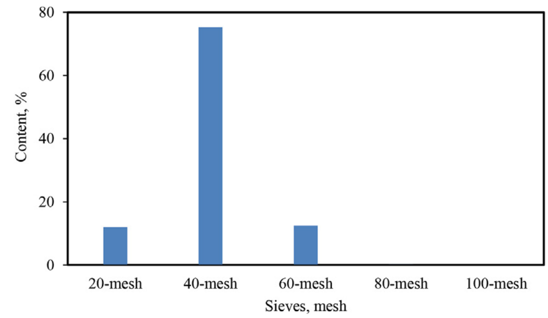

Fig. 1. Size distribution of preformed particle gel (Song et al., 2018).

2.1.2. Semi-transparent fracture model

The semi-transparent fracture model was constructed of two acrylic plates with a rubber O-ring between them. Bolts, nuts, and shims were used to fix the two plates and control fracture width. One of the acrylic plates was transparent for visual tracking. On the other plate, a long square packet (with a dimension of 2 inches wide, 9 inches long, and 1 inch deep) was drilled in the center and a piece of Roubidoux sandstone slab, obtained from central area of Missouri, was casted into this pocket using epoxy. This enabled us to study gel movement with the existence of sandstone rough surface and the leakoff in the rock matrix of a real fracture system. Before the fabrication of fracture model, the sandstone slab was firstly vacuumed and then saturated with brine. The fracture model had three sections of equal length that were delineated by four fracture pressure taps on the transparent acrylic plate. On one side of this plate, a hole functioned as an inlet for the injection; on the other side, another hole provided an outlet to discharge fluids. The pressure transducers were connected to the pressure taps to monitor the pressure changes along the fracture. The effluent from the fracture and matrix was separated and recorded through different fittings during the experiment. Fig. 2 shows (a) the schematic diagram and (b) the picture of the semi-transparent model, respectively. Four fracture widths (0.05, 0.1, 0.15, and 0.5 cm) were used to examine the effect of fracture size on gel placement. The internal diameter of the tube leading into the fracture was approximately ¼ inches, and its length was 4 inches. A metal connector with an internal diameter of ⅜ inches and a length of less than 1 inch was used to discharge the fluids from the outlet.

2.2. Experimental procedure

Brine was first injected into the fracture model, and then fully swollen PPG was extruded into the fracture model by an Isco pump