Fuel 231 (2018) 479–488

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Full Length Article

Micro-particle gel transport performance through unconsolidated sandstone and its blocking to water flow during conformance control treatments

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ARTICLE INFO

Keywords:
Micro-particle gel transport
Conformance control
Unconsolidated sandstone
Gel particle retention
Passing criteria

ABSTRACT

High-permeability streaks, fractures, conduits, and fracture-like features can expedite an undesirable water channeling and early water breakthrough during water flooding. Micro-preformed particle gel (PPG) is one of the commercial gels invented exclusively to plug such features to reduce excess water production and increase oil production. This paper reports the results of laboratory experiments that studied the PPG's injection and placement mechanism through unconsolidated sandstone cores. Extensive experiments were conducted to examine the effect of the sand permeability, PPG size, concentration, and water salinity on the PPG injection process, passing criteria, and plugging efficiency to water flow. A two foot sand pack model with four pressure taps was designed to monitor PPG transport and plugging performance. The results showed that the PPG propagated deep into the unconsolidated sandstone. Fully swollen gel particles had better injectivity than partially swollen particles with a larger diameter size; particle strength was more dominant in influencing particle movement than was particle size. The injection pressure increased as the PPG concentration, water salinity, and gel particle size increased. High gel particle injection pressure was measured in the front part of the unconsolidated sandstone as a result of gel particle retention. The retention was controllable by selecting proper gel particle strength, concentration, and size. PPG transport through unconsolidated sand exhibited four patterns of injection processes: low gel particle retention and pass; high gel particle retention and pass; high gel particle retention, breaking, and pass; and gel particle accumulation and plug. The micro-gel particle's blocking efficiency to water flow increased as the PPG strength, size, and concentration increased. The PPG placement mechanism, such as washout, was also found to considerably affect the water injection flow processes. The results of this laboratory experiment will aid in the selection of future conformance control candidates and also optimize the particle gel treatment design for large-scale field projects.

1. Introduction

Water cut continues to rise as water flooded oil fields become more mature. The increase in water cut results in higher levels of corrosion and scales, an increased load on fluid handling facilities, more environmental concerns, and a shorter economic life for the well. Water control is becoming a major challenging task to many oil and gas companies. Water channeling, one of the primary reservoir conformance problems, is caused by reservoir heterogeneities that lead to the development of high-permeability streaks. These streaks include open fractures and fracture like features, such as caves, worm holes, and conduits [7]. These high-conductivity areas inside the reservoir only occupy a small fraction of the reservoir but will capture a significant portion of injected water. As a result, large amounts of oil remain unswept as a large water flood will bypass oil-rich unswept zones/areas.

Gel treatments have been proven to be a cost-effective chemical conformance control technology to reduce the fluid flow in these large opening features. The application of these technologies can not only control water production but also significantly increase the oil production and extend the economic life of a reservoir. A gel's treatments success depends heavily on the gel's ability to reduce the conductivity of these large-channel features. Thus, understanding both the mechanism and the factors affecting the gel injection and the gel's ability to resist water flow through these features are the main keys to a successful conformance control treatment [7]. Numerous studies have been conducted in an attempt to evaluate in-situ gel propagation through high permeability streaks and fractures. [14–18] studied both bulk gel placement and the mechanism behind gel propagation through fracture systems. Sydansk et al. [19] characterized the transport of partially

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https://doi.org/10.1016/j.fuel.2018.05.099
Received 6 February 2018; Received in revised form 18 May 2018; Accepted 19 May 2018
Available online 30 May 2018
0016-2361/

formed gels in fractures. Ranganathan et al. [13] found a significant retention of polyacrylamide/aluminum citrate colloidal dispersion gel (CDG) in the first part of the sand pack. They also found that CDG did not propagate deeply into the sand pack to give in-depth permeability reduction. Smith et al. [21] investigated CDG propagation through a sand core with permeabilities ranging from 1000 to 3000 md. They showed that permeability reduction was observed across the core, but the development of in-depth permeability reduction could not be confirmed. They interpreted this result to mean that the CDG gallant flowed through the core prior forming gel in a manner similar to that of uncrosslinked polymer. Lu et al. [11] evaluated CDG propagation through homogenous artificial cores. They showed that a significant retention of CDG occurred in the first section of the cores but they did not verify that CDG caused in-depth permeability reduction across the cores. Al-Assi et al. [1] evaluated CDG propagation through a sand pack permeability of approximately 10 Darcy. They showed that a high flow resistance developed slowly across the sand pack, beginning at the inlet section, demonstrating formation and retention of gel aggregates in the sand pack. They also reported that the retention of the gel aggregates limits the in-depth treatment of a 10-darcy porous matrix rock to a relatively short distance. The gel resistance to water flow was also studied by many researchers. Ganguly et al. [6] evaluated the immature gel stability when it was subjected to an imposed brine pressure. They observed that the gel ruptured when brine pressure was applied at the inlet. Substantial resistance to brine flow remained after the gel was ruptured, but this resistance decreased with continuous brine injection. Seright [18] evaluated how mature Cr (III)-acetate-HPAM gel wash out was affected by the pressure gradient and other factors. Seright found that the mechanism of gel failure involved the displacement of relatively mobile gel from wormholes. Brattekas et al. [3] studied the rupture pressures (1) after the placement of gelant crosslinked in-situ, and (2) of mature gel in open fractures. They found that the rupture pressures achieved after the placement and in-situ crosslinking of immature gel were comparable to the rupture pressures achieved after mature-gel placement, but the former were less predictable.

Few studies have been conducted to investigate preformed particle gel injection and placement in high permeability streaks and fractures. Bai et al. [2] investigated PPG transport mechanisms through porous media; they used etched glass micromodels and sand pack macromodels. They found that PPG propagation through porous media exhibited different injection patterns of behavior. They also reported that the PPG propagation pattern of behavior was dependent on the gel strength, threshold pressure, and pore throat structure. Zhang and Bai [20] investigated PPG extrusion through fractures. They observed that the PPG propagated like a piston when the PPG size was larger than or close to the size of the fracture width. Imqam et al. [7] investigated PPG injection and placement mechanisms through conduits or large channels, under conditions where the channel opening size was larger than, equal to, or smaller than the swollen PPG size. Their results indicated that the PPG strength affected injectivity more significantly than did the particle opening ratio. Additionally, the size of the PPGs decreased during their transport though the channels due to both dehydration and breakdown. Subsequent work was conducted by Imqam and Bai [10] to further understand the resistance of PPGs to water flow. They designed a large transparent channel to investigate how factors such as PPG strength, PPG size, and the load pressure effect on the PPG placement behavior. They reported that the PPG did not fully block the channel but rather formed gel pack permeability along the channel model. Imqam et al. [9] investigated the effect of water and oil flow on PPG behavior. They noticed that the PPG always reduced the fracture permeability to water much more than to oil permeability. They also reported that higher oil viscosity had better disproportionate permeability reduction than low oil viscosity. Elsharafi and Bai [4], Elsharafi and Bai [5] and Imqam et al. [8] conducted a study on the effect of PPG placement on low permeability formations. They noticed that the PPG formed a permeable gel filter cake on the surface of low permeability rocks.

Table 1
Ppg swelling ratio and strength in 0.05% and 1% nacl.

No	Brine Concentration: C, NaCl%	Swelling Ratio	Gel Strength: G‘,pa
1	0.05	165	515
2	1	50	870

Based on our knowledge, no efforts have been done yet to evaluate processes such as PPG injection, retention, wash out, and resistance to water flow through unconsolidated sandstone streaks. The objective of this paper was to conduct an experimental core flooding to evaluate factors such as PPG concentration, strength, size, and unconsolidated sandstone permeability on both PPG injection and placement mechanisms through unconsolidated sandstone streaks.

2. Experimental description

The following are descriptions of the materials and equipment used to investigate the mechanisms of PPG propagation through unconsolidated sandstone streaks.

2.1. Preformed particle gel (PPG)

A superabsorbent polymer was used as a PPG to conduct the experiments. Dry particles with sizes of 75 µm and 150 µm were swollen in a 1% sodium chloride (NaCl) brine concentration. Gel concentrations of 800 and 2000 ppm were used. Table 1 lists the PPG swelling ratios and PPG strength measurements for PPGs swollen in 0.05% NaCl and 1% NaCl. PPGs swollen in the low brine concentration (0.05% NaCl) were more swellable and weaker than PPGs swollen in the high brine concentration (1% NaCl).

2.2. Brine concentration and oil viscosity

Both 0.05% and 1 wt% NaCl were used for brine injection and to prepare the swollen PPGs. Oil with a viscosity of 37 cp at 70 °F was used to saturate the sand pack model.

2.3. Magnetic stirring vessel

An accumulator with a 1200 ml capacity and a maximum adjusted impeller speed of 1800 r/min was used to inject PPGs into a high permeability sand pack model. The impeller was placed at the bottom of the accumulator so that the PPGs remained dispersed in brine before they were injected into the model.

2.4. Unconsolidated sandstone

Silica sand was used to obtain different permeability sand packs. A vibrator machine was used to pack the sand carefully to obtain the desired permeability. A range of mesh sizes was used to obtain an approximate sand permeability of 65.4 and 26.5 Darcy. Table 2 illustrates

Table 2
Sand pack permeability and ppg properties used in each experiment.

Experiment	Sand Pack Permeability, Darcy	PPG Concentration, ppm	NaCl Concentration, %	PPG Size, micron
1st Experiment	26.5	2000	1	75
2nd Experiment	65.4	2000	1	75
3rd Experiment	26.5	800	1	75
4th Experiment	26.5	2000	0.05	75
5th Experiment	26.5	2000	1	150