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Review Article

A review of crosslinked fracturing fluids prepared with produced water

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ABSTRACT

The rapidly increasing implementations of oilfield technologies such as horizontal wells and multistage hydraulic fracturing, particularly in unconventional formations, have expanded the need for fresh water in many oilfield locations. In the meantime, it is costly for services companies and operators to properly dispose large volumes of produced water, generated annually at about 21 billion barrels in the United States alone. The high operating costs in obtaining fresh water and dealing with produced water have motivated scientists and engineers, especially in recent years, to use produced water in place of fresh water to formulate well treatment fluids. The objective of this brief review is to provide a summary of the up-to-date technologies of reusing oilfield produced water in preparations of a series of crosslinked fluids implemented mainly in hydraulic fracturing operations. The crosslinked fluids formulated with produced water include borate- and metal-crosslinked guar and derivatized guar fluids, as well as other types of crosslinked fluid systems such as crosslinked synthetic polymer fluids and crosslinked derivatized cellulose fluids. The borate-crosslinked guar fluids have been successfully formulated with produced water and used in oilfield operations with bottomhole temperatures up to about 250 °F. The produced water sources involved showed total dissolved solids (TDS) up to about 115,000 mg/L and hardness up to about 11,000 mg/L. The metal-crosslinked guar fluids prepared with produced water were successfully used in wells at bottomhole temperatures up to about 250 °F, with produced water TDS up to about 300,000 mg/L and hardness up to about 44,000 mg/L. The Zr-crosslinked carboxymethyl hydroxypropyl guar (CMHPG) fluids have been successfully made with produced water and implemented in operations with bottomhole temperatures at about 250+ °F, with produced water TDS up to about 280,000 mg/L and hardness up to about 91,000 mg/L. In most of the cases investigated, the produced water involved was either untreated, or the treatments were minimum such as simple filtration without significantly changing the concentrations of monovalent and divalent ions in the water. Due to the compositional similarity (high salinity and hardness) between produced water and seawater, crosslinked fluids formulated with seawater for offshore and onshore jobs were also included. The crosslinked guar and derivatized guar fluids have been successfully formulated with seawater for operations at bottomhole temperatures up to about 300 °F. Operating costs have been significantly reduced when produced water or seawater is used to formulate fracturing fluids in place of fresh water. With various challenges and limitations still existing, the paper emphasizes the needs for new developments and further expansion of produced water reuse in oilfield operations.

1. Introduction

With the implementations of oilfield technologies such as horizontal wells and multistage hydraulic fracturing in unconventional formations, demand for fresh water used in hydraulic fracturing is going up continuously. The ever increasing demands and rising cost of fresh water have motivated the industry to use

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less ideal water sources such as produced water in place of fresh water in oilfield operations. Produced water is defined as the water trapped in reservoir and produced along with oil and gas from wells in oilfield [1]. Produced water may also include other types of low-quality water available in or near oilfield such as flowback water [2–4] or surface water from rivers, lakes, ponds, or wells [5]. Produced water shows various levels of total dissolved solids (TDS) that include inorganic salts, mostly chlorides and sulfates of sodium, calcium, and magnesium, and water-soluble organic matters in a given volume of water. Produced water from some field locations can have TDS values as high as about 400,000 mg/L [6]. As a comparison, typical seawater has TDS at about 35,000 mg/L [7].

Though produced water reuse has been going on for some years in the petroleum industry, fracturing fluids nowadays are normally formulated with fresh water [8]. This is because high levels of salinity and hardness in produced water can readily pose difficult and costly challenges for a wide range of fracturing fluid systems. Some companies mitigate the produced water damage by removing significant percentages of divalent ions or even most salts from produced water. However, it is usually cost-prohibitive to treat high-TDS produced water to such an extent that it can be directly used to formulate stable fracturing fluids originally designed for fresh water. On the other hand, most of the produced water generated in oilfield nowadays is not reused but rather disposed of through, for example, injection in underground disposal wells [3] that can be expensive, costing about US$0.3–10 per barrel (bbl; 1 bbl = 42 gallons or 159 L) [9].

Hydraulic fracturing is a stimulation treatment performed on oil and gas wells to improve well productivity in low-permeability reservoirs or damaged wells. In hydraulic fracturing, large volumes of fracturing fluids are pumped into the wellbore with certain pumping rates. When the pressure generated from the fluids exceeds the fracture pressure, formation rocks break down to form fractures into which fracturing fluids are injected. Prepad and/or pad fluids without proppant are usually pumped first to initiate and generate fracture geometries. Proppant-laden fracturing fluids are then injected after the pad fluids to further increase fracture length and width. Proppant particles are transported into the factures thus created. Once the pumping is finished and the pumping pressure withdraws, the fractures close onto the proppant pack, but are kept open by the proppant for hydrocarbons to efficiently flow out. After the fracturing process, the fracturing fluids are broken into low-viscosity thin liquid by enzyme breakers or oxidative breakers such as ammonium persulfate to flow back to the surface. This way, the damage caused by the fracturing fluids to the formation and proppant pack is minimized, and the proppant particles can stay behind in the fractures without flowing back as the broken fluid is too thin now to carry the proppant out of the fractures [10].

The initial hydraulic fracturing treatments were performed in the 1940s with oil-based fluids consisting of gelled hydrocarbons. Water-based fracturing fluids started in the 1950s [11], and have become the predominant type of hydraulic fracturing fluids since then [12]. As water-based fracturing fluid systems are more cost-effective, they become the safer alternatives to the oil-based fluids. Water-based fluids typically include slickwater, linear (uncrosslinked) fluids, and crosslinked fluids. Other types of water-based fracturing fluids include viscoelastic surfactant (VES) fluids [13,14]. An effective fracturing fluid should possess a number of desired characteristics such as easy preparation, low fluid loss, sufficient viscosity for proppant transport, low friction pressure, sufficient shear resistance, low formation and proppant pack damage, good reservoir compatibility, and reasonable cost, etc. More comprehensive information can be found in a recent review conducted by Al-Muntasheri [15] about the water-based fracturing fluids over the last decade.

Slickwater is made up mostly of water, and typically contains friction reducer such as acrylamide-based polymers and copolymers to reduce friction pressure in surface lines and well casing during pumping. With low viscosity close to that of fresh water, slickwater is usually pumped at high rates (>60 bpm) to generate narrow fractures with low dosages of proppant, typically on the order of 0.25–1 ppa (pound per gallon added) [16].

Linear fluids are based on uncrosslinked solutions of polymers such as guar, guar derivatives, cellulose, cellulose derivatives, other polysaccharides such as xanthan or diutan, or synthetic polymers. Most of the water-based fluids are formulated with guar and guar derivatives [17]. Guar is a high molecular weight polymer consisting of a mannose backbone and galactose side chains, with the average molecular weight in the range of about 200,000–2,000,000 Da [18]. Depending on the polymer dosage, the viscosity of a linear fluid can be several orders of magnitude higher than that of slickwater, possessing therefore much better proppant suspension and transport capability.

When a crosslinker, typically made of borate or metal compounds such as zirconium (Zr) and titanium (Ti) compounds, is added to a linear fluid, the crosslinking species form bonding among polymer chains, resulting in a viscous crosslinked fluid with enhanced gel viscosity and improved high temperature stability. Compared with linear fluids, crosslinked fluids show improved performance without increasing the polymer concentration. For example, crosslinked fluids have a larger capacity to suspend and transport proppant particles than the corresponding uncrosslinked fluids with the same polymer dosage. The first patent on the borate-crosslinked guar fluids (US patent 3,058,909) was filed in 1957 and granted in 1962 [19]. Guar fluids are still the most widely used fluids in fracturing operations due to their low cost, performance flexibility, and shear stability [15,20,21]. In the early 1970s, metal-crosslinked water-based fracturing fluids were implemented for jobs at higher bottom-hole temperatures. The most common metal crosslinkers are based on the zirconium and titanium compounds. The metal crosslinkers are usually complexes of zirconium or titanium with certain organic ligands or chelators, such as zirconium ammonium lactate, zirconium acetate, or titanium triethanolamine [21].

Slickwater or hybrid fluid system is typically used to create more complex fracture networks than conventionally used crosslinked fluids [22,23]. However as mentioned earlier, due to their intrinsic low viscosity, slickwater fluids have low capability of proppant transportation and have to be pumped at high rates. The high pumping rate in slickwater jobs can significantly shorten the service lifetime of pumping equipment. To reduce the equipment breakdown and to enhance the proppant transport and placement, hybrid treatments are implemented so as to maximize the benefits of both slickwater treatments and linear/crosslinked fluid treatments for unconventional reservoirs. During a hybrid treatment, slickwater injection is carried out first to generate complex fracture networks, followed by linear and/or crosslinked fluids with much better capability to transport and place proppant. Such hybrid jobs have grown rapidly for horizontal wells in unconventional formations in recent years [23].

The elevating costs of produced water disposal and fresh water purchase have given oilfield services companies and operators the motivation to reuse as much produced water as possible, without the expensive treatments to the produced water. More specifically, for hydraulic fracturing operations, the