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Full Length Article

Experimental study of combining low salinity water flooding and preformed particle gel to enhance oil recovery for fractured carbonate reservoirs

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ABSTRACT

Oil recovery from carbonate reservoirs is usually low due to their extreme heterogeneity caused by natural fractures and the nature of the oil-wet matrix. Low salinity water flooding (LSWF) and preformed particle gels (PPG) control conformance are two novel technologies that have recently drawn great interest from the oil industry. Theoretically, LSWF can only increase displacement efficiency, and it has little or no effect on sweep efficiency; PPG can plug fractures, they can improve sweep efficiency, but they have little effect on displacement efficiency. We developed a cost-effective, novel, enhanced oil recovery (EOR) technology for carbonate reservoirs by coupling the two technologies into one process. The objective of this paper is to provide a comprehensive understanding of the combined technology and to demonstrate how the coupling method can improve oil recovery. The oil-wet carbonate cores provided a higher improved oil recovery than water-wet carbonate cores during LSWF. The decrease in fracture width resulted in a higher oil recovery factor. Compared to traditional bulk gel treatments, PPG forms stronger plugging but will not form an impermeable cake in the fracture surface; therefore, PPG allows low salinity water to penetrate into the matrix to modify its wettability, thereby producing more oil from the matrix. Results also show that oil recovery increased by 10% during LSWF after the second water flooding. Additionally, when PPGs were injected, another 4% of oil recovery was gained. As a result, the combined LSWF and PPG increased oil recovery by 18%. A full-factorial experimental design was performed to investigate the influence of the PPG-placed injection pressure (which refers to the maximum pressure used to inject PPG for each experiment), water salinity, and fracture width. Experimental results tell that PPG-placed injection pressure is the factor that strongly influences both oil recovery factor and residual resistance factor; fracture width is the least influential factor among the three. Experimental results prove that the coupled method bypasses the limitations of each method when used individually and improves both displacement and sweep efficiency.

1. Introduction

EOR methods offer promising approaches to recover a significant portion of remaining oil which is about two-thirds of the oil in place and cannot be recovered by conventional technologies. Excess water production and low oil production rates are two major issues that lead to early well abandonment and unrecoverable hydrocarbon in mature wells. Preformed particle gels (PPG) control conformance and low salinity water flooding are two novel EOR technologies that have recently gained favorable attention by the oil industry.

Preformed particle gels have recently been developed and applied to improve the sweep efficiency of water flooding. PPG is made of specific kind of superabsorbent polymers. Their size can be controlled in nanometer, micro-meter and also millimeter ranges. PPG is able to overcome some drawbacks inherent in in-situ gelation systems such as lack of gelation time control, gelling uncertainty due to shear degradation, chromatographic fractionation, or dilution by water formation [9,5,6]. A preformed gel is formed at a surface facility before injection, and is then injected into a reservoir; thus, no gelation occurs in the reservoir. These gels usually have only one component during injection, and little sensitivity to physicochemical conditions in a reservoir, such as pH, salinity, multivalent ions, hydrogen sulfide, and temperature [5,6]. Current commercially available particle gels come in various sizes, including micro- to millimeter sized preformed particle gels (PPGs) [5,6,32], microgels [35], pH sensitive crosslinked polymers [2,12], and swelling submicron-sized polymers [23,11]. Their major differences lie in the particle size, swelling time, and swelling ratio. Published documents show that PPG, microgels, and submicron-sized polymers have

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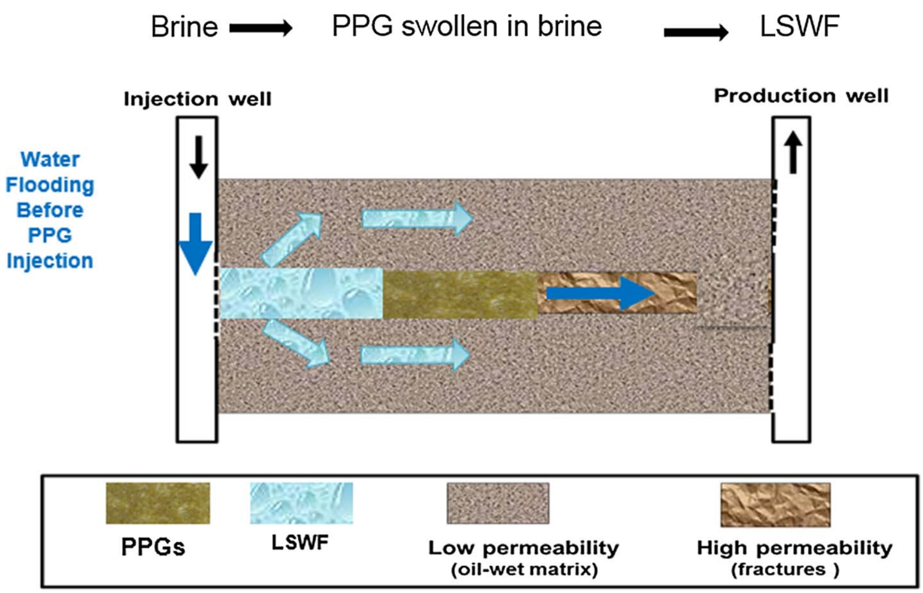

Fig. 1. Schematic of the proposed mechanism.

been economically applied to reduce water production and improve oil recovery in mature oil fields. Microgels were applied to about 10 gas storage wells to reduce water production [35]. Submicron-sized particles were applied to more than 60 wells [10]. A Swelling Polymer for In-depth Profile Modification: Update on Field Applications. Presented at SPE Applied Technology Workshop of Chemical Methods of Reducing Water Production. San Antonia [10]). Millimeter-sized PPGs can preferentially enter into fractures or fracture-feature channels while minimizing gel penetration into unswept zones and matrixes when millimeter-sized particle gels are used, and they have been applied in nearly 10,000 wells in water floods and polymer floods worldwide to reduce the permeability of fractures or super-permeable channels [7].

Low salinity water flooding has been widely investigated to reduce the residual oil saturation in swept areas and thus improve oil recovery. The encouraging effect of low salinity water on oil recovery can be traced back to [20]. He observed an increase in oil recovery by injection of fresh water compared to sea water injection in sandstone core samples. However, its EOR potential was not recognized until Morrow, and his co-workers published a series of related works from 1991 to 1999 [16,17,33,31,30]. Since then, many companies and research organizations have investigated how water salinity and compositions affect oil recovery and their mechanisms for sandstone and carbonates. Extensive laboratory experiments have demonstrated that low salinity water can improve oil recovery for both sandstone and carbonate reservoirs [26]. Zhang et al. [36] reported that high salinity water injection into chalk formations increased oil recovery up to 40% original oil in place (OOIP). Lager et al. [18] and McGuire and Chatham [21] reported that low salinity water-floods could increase recovery up to 40% OOIP. In sandstone formations, a few field applications have also demonstrated the technology can further reduce residual oil saturation compared to normal water flooding [21,25,19,34]. It is reported that the degree of oil recovery improvement relies on multicomponent ion exchange, clay contents, formation water composition, oil composition, and initial water saturation. A few mechanisms have been proposed to explain the positive effect, including: migration of fines [30], interfacial tension reduction [21], multi-component ionic exchange [18], PH driven wettability change [18,21], double-layer expansion [19], desorption of organic material from clay surface [4], wettability alternation [34], mineral dissolution [1], and microscopically diverted flow [27,28]. These mechanisms lead to modification of rock wettability from oil-wet or intermediate/water wet to water wet; therefore, residual oil saturation is reduced, and ultimate oil recovery is improved. In other words, LSWF achieves better oil recovery by improving microscopic displacement efficiency.

Oil recovery is the product of displacement efficiency (ED) and sweep efficiency (ES). LSWF can increase displacement efficiency but has little or no effect on sweep efficiency, and PPG treatment can only be used to plug fractures or high permeable channels to improve sweep efficiency and has little effect on displacement efficiency. The research will investigate the idea of coupling PPG treatment and LSWF injection into one process; thus, bypassing the limitations of each method when they are used individually. It is expected that the combined method will improve both displacement and sweep efficiency and thus provide a more cost-effective EOR method.

The objective of this study is to investigate whether the proposed method can be used to improve oil recovery from carbonate reservoirs. Laboratory experiments were conducted to evaluate the effect of four key parameters on oil recovery using designed carbonate fracture models, including the salinity of injection water, fracture width, wettability, and PPG placing pressure,

2. Mechanisms of the proposed method

The injection process of this integration technique can be performed in the sequential injection mode. PPGs are injected first to block the fractures; then, low salinity water is injected. The PPG block fractures to prevent low salinity water from attaining early breakthrough. PPG will divert low salinity water into a matrix to produce oil from the unswept matrix. Fig. 1 shows the schematics of the proposed EOR technique.

3. Experiments

3.1. Materials

PPGs: A super absorbent crosslinked polymer with a mesh size of 20–30 was used as the preformed particle gel for this study. The particle was synthesized by a free radical process using acrylamide, acrylic acid, and N,N'-methylene-bisacrylamide [5,6] Muhammed et al. [22].

Brine: Sodium chloride (NaCl) was used to prepare different concentrations of brine. It was used for water flooding and to prepare the swollen PPG. Three brine concentrations (1, 0.1, and 0.01 wt% NaCl) were used for the experiments.

Crude oil: A light crude oil (York crude oil) was used with the properties of API 36°, a density of 0.845 g/cc, and a viscosity of 9.25 cp. The crude oil properties were measured at 77 F. The acid number was