Nanoparticles Aid Oil Recovery During Alternating Injection

Although the potential of nanoparticles (NPs) to improve oil recovery is promising, their effect during alternating injection is still uncertain. The main objective of the authors' study is to investigate the best recovery mechanisms during alternating injection of NPs, low-salinity water (LSW), and surfactant and transform the results into field-scale technology. The outcome of these experiments revealed that tertiary injection of NPs results in additional oil recovery beyond the limits of LSW.

Introduction

A series of coreflooding experiments was conducted using several cores with an effective permeability of approximately 1 md to the brine at a temperature and pressure of 70°C and 3,000 psi. The study performs four different alternating injections of NPs with LSW and surfactant to determine optimal oil recovery. The wettability of the rock and fluid and the interfacial tension (IFT) of oil and water are measured to understand the mechanisms of interactions between the fluids and the reservoir rock.

Materials

A 12×12×12-in. block taken from an outcrop of Indiana limestone reservoir was purchased for this study. Four core plugs with a diameter of 1.5 in., used for the coreflooding experiments, were selected from this block. A synthetic 100,000-ppm (10 wt%) brine was prepared in the laboratory by dissolving sodium chloride (NaCl) and calcium chloride with a ratio of 4:1 in deionized water. The crude oil used in this study was a volatile oil (properties are described in Table 2 of the complete paper) obtained from the Permian Basin in Texas.

Injected Fluids. A 10,000-ppm (1 wt%) LSW was prepared by diluting the synthetic brine 10 times. The surfactant solutions were prepared from an anionic sodium dodecyl sulfate (SDS) surfactant. A 1,000-ppm (0.1 wt%) surfactant solution used throughout the experiments was selected on the basis of the estimated critical micelle concentration of 600 to 2,240 ppm for SDS and nanofluid/NaCl. The concentration of silica NPs used in this study was 500 ppm (0.05 wt%). The nanofluids were prepared either as a simple solution or as a mixture with other chemicals to make a concentration of 500-ppm silica NPs.

Coreflooding System. The established coreflooding system used for this experimental study was custom-made to determine the oil recovery and the relative permeabilities at steady-state and unsteady-state flows. However, the focus of this study is to investigate the effect of silica NPs on oil recovery. The schematic diagram of the coreflooding system is shown in **Fig. 1.**

Methods

The complete paper describes the methodology for investigating effective porosity, water saturation, and core aging; this section of the synopsis will concentrate on the methodology used in investigating oil recovery.

The oil recovery for this study was designed to mimic the process of recovery used by the oil industry. It is divided into secondary and tertiary methods. To account fully for the effect of silica NPs during the oil recovery, the following four different cases of injecting silica NPs were considered.

Case 1: LSW/NPs/Surfactant (LNS Cycle). LSW was injected at constant rates as described for brine until no oil was recovered before switching to injection of NPs. The same procedure was repeated for surfactant. The cycle was repeated with injection of LSW and the solution of NPs after injection of surfactant. Core Plug A was used during this cycle.

Case 2. LSW/Surfactant/NPs (LSN Cycle). LSW was injected as described in the previous cycle before surfactant and NPs. The process was concluded with the injection of LSW after NPs. This cycle was applied to Core Plug B.

Case 3: Mixture of LSW and NPs/Surfactant (MLNS Cycle). The process started and ended with the injection of a mixture of 10,000-ppm LSW and 500-ppm NPs (LN) into the core as described in the previous cycles. Core Plug C was used for this experiment.

Case 4: LSW-Mixture of NPs and Surfactant (LMNS Cycle). LSW was injected into the core before the injection of a mixture of 500-ppm NPs and 1,000-ppm surfactant (NS). The process began and ended with the injection of LSW. The same procedure was used throughout all cases. The experiment was performed with Core Plug D.

Results

Coreflooding Experiments. The effect of silica NPs during enhanced oil recovery was taken into consideration by

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conducting coreflooding experiments with silica NPs on four different tight carbonate core plugs at the same conditions discussed previously. The cycles of injections were applied to four different core plugs selected from the outcrop of the Indiana limestone reservoir. The cores were initially flooded with the synthetic brine until no more oil was produced during the secondary recovery. Then, the alternating injection of NPs, LSW, and surfactant for tertiary recovery in the core plug was performed. These injection cycles are detailed in the complete paper.

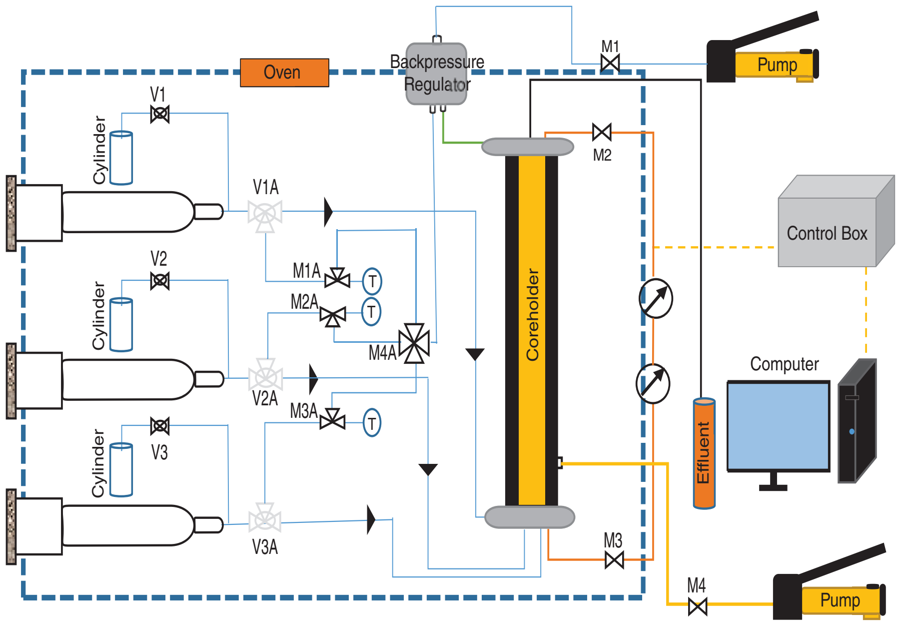

Fig. 1—Schematic of coreflooding apparatus used for the experimental study.

IFT and Wettability Variation. The IFT measurement of crude oil and injected fluids was conducted at a temperature and pressure of 70°C and 3,000 psi to determine the effect of silica NPs on LSW and surfactant. The contact-angle measurement to determine the rock/fluid interaction was conducted to mimic the four different cycles of injections performed on the coreflooding system. The variations in the contact angle with different injected-fluid cycles are presented graphically in the complete paper.

Analysis of Mechanisms

The contact-angle-analysis results show that the injection of the first NPs during the LNS cycle shifted the wettability slightly toward more water-wet than was seen with LSW. This change in wettability is attributed to the transient interaction between NPs and the fluid (brine) present in the pores. The amorphous structure of silica NPs formed in the pores detaches the oil droplet from the rock surface faster than LSW and forms an interface with the rock surface, oil, and brine to alter wettability. The formation of the amorphous structure of silica NPs in the pores is reduced at high flow rate because of limited contact with the initial fluid in the pores and the threshold concentration of the NPs.

The injection of a surfactant solution increases the formation of an amorphous structure of NPs in the reservoir pores because of an increase in the concentration of aqueous solution. The adsorption of NPs on the rock surface is increased by the surfactant present in the pores, which leads to coalescence and aggregation. However, the effect of IFT is dominant during the injection of surfactant. The accumulated layers of NPs on the rock surface are removed by the injection of LSW or surfactant to reduce formation damage.

The injection of LSW and NPs after injecting surfactant during the LNS cycle shifted the wettability toward oil-wet. The differential pressure across the core also increased during the second injection of NPs. Therefore, the layers of NPs formed on the rock surface were increased. The formation of layered NPs on the surface of rock and the dissolution of limestone are assumed to occur at the same rate because no significant increase in differential pressure during the LSN cycle exists. Additionally, the areal sweep efficiency of the solution in the core plug was increased by the mixture of brine, surfactant, and NPs. Therefore, it is inferred that the oil recovery during this phase of injection was caused by viscosity modification. The procedure adopted during the injection prevented snap-off and trapping of the oil phase.

The mechanisms of recovery presented in this study for the four cycles were similar, but the wettability varied in different cycles. During the LSN cycle, the change in wettability toward water-wet during the injection of NPs was relatively small compared with the first injected solution of NPs during the LNS cycle.

A similar response in wettability was observed during the MLNS cycle. However, the wettability was improved during the LMNS cycle. A mixture of NPs and LSW or surfactant reduced the IFT. The wettability of a mixture of nanofluid and LSW slightly varied from the wettability of LSW, implying that the initial interaction between LSW and NPs reduced its ability to alter wettability.

Conclusions

- Sequential injection of NPs after LSW alters the wettability toward more water-wet as observed in the LNS cycle.
- Reduction in IFT when NPs are dispersed in LSW, in addition to wettability alteration, is responsible for the higher recovery compared with other sequences of injection.
- An improved efficiency in the areal sweep, in addition to wettability alteration and reduction in IFT by NPs dispersed in surfactant, is responsible for improved oil recovery during an LMNS cycle.
- Alternating injection of the fluids during LNS and LSN cycles is proved effective for NPs because of the interaction of the individual injected fluid with the reservoir rock.
- The procedure presented in this study not only improved oil recovery but also reduced formation damage by NPs, as observed during different cycles. **JPT**