

Heavy and Thermal Oil Recovery Production Mechanisms

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Abstract

This technical progress report describes work performed from July 1 through September, 2003 for the project "Heavy and Thermal Oil Recovery Production Mechanisms," DE-FC26-00BC15311. In this project, a broad spectrum of research is undertaken related to thermal and heavy-oil recovery. The research tools and techniques span from pore-level imaging of multiphase fluid flow to definition of reservoir-scale features through streamline-based history-matching techniques.

During this period, work focused on completing project tasks in the area of multiphase flow and rock properties. The area of interest is the production mechanisms of oil from porous media at high temperature. Temperature has a beneficial effect on oil recovery and reduces residual oil saturation. Work continued to delineate how the wettability of reservoir rock shifts from mixed and intermediate wet conditions to more water-wet conditions as temperature increases. One mechanism for the shift toward water-wet conditions is the release of fines coated with oil-wet material from pore walls. New experiments and theory illustrate the role of temperature on fines release.

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List of Graphical Materials

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Introduction

The objective of this research project is to improve the recovery efficiency from difficult to produce reservoirs including heavy-oil and fractured low permeability systems. This objective is accomplished by developing laboratory techniques and apparatus for studying multiphase flow properties in fractured and unfractured porous media, identifying oil production mechanisms from the pore to the core to field scale, and translating this understanding into mathematical models incorporating newly understood physics.

The project is divided into 5 main areas. These projects and their goals include:

1. Multiphase flow and rock properties—to develop better understanding of the physics of displacement in porous media through experiment and theory.
2. Hot fluid injection—to improve the application of nonconventional wells for enhanced oil recovery and elucidate the mechanisms of steamdrive in low permeability, fractured porous media.
3. Mechanisms of primary heavy oil recovery—to develop a mechanistic understanding of so-called "foamy oil" and its associated physical chemistry.
4. In-situ combustion—to evaluate the effect of different reservoir parameters on the in-situ combustion process.
5. Reservoir definition—to develop and improve techniques for evaluating formation properties from production information.

Executive Summary

The project is scheduled for completion December 31, 2003. As such, work in many of the task areas is winding down. Work continued in Area 2 and papers were prepared for the SPE International Thermal Operations and Heavy Oil Symposium and Western Regional Meeting to be held March 16 to 18 in Bakersfield CA. Papers representing research results in Area 1, Area 2, and Area 3 are under preparation.

Work in Area 2 centered on understanding the role of fines release and in turn the effect of fines release on porous medium wettability. Predictions are presented in the form of isotherm maps. They are confirmed experimentally by core waterfloods performed in Berea sandstone at temperatures ranging from 20 to 200°C. Fines mobilization occurs repeatably at a particular temperature that varies with solution pH and ionic strength. A scanning electron microscope (SEM) was used to analyze composition of the effluent samples collected during experiments. This study shows that temperature is a decisive factor in fines release and the temperature at which the detachment of fines occurs is well predicted.

Area 1. Multiphase Flow and Rock Properties

Work in this area is complete with the exception of the presentation of a technical paper (Rangel-German and Kovscek, 2003) at the upcoming Society of Petroleum Engineers Annual Technical Conference and Exhibition. Final results and a summary will be presented in the Final Technical Progress Report.

Area 2. Hot Fluid Injection

During the past quarter work in this area has centered on preparing a manuscript for presentation at the Society of Petroleum Engineers International Thermal Operations and Western

Regional Meeting regarding results in the area of oil recovery mechanisms resulting from steam injection into low permeability rock (Hoffman and Kovscek, 2004). A second area is to improve our understanding of the shift in wettability of reservoir rocks subjected to thermal recovery. This work is detailed next.

Reservoir rocks are thought to become more water wet during thermal recovery. The consequence of a shift toward water wetness is that steam and steam condensate become more effective displacement agents and the rock matrix imbibes water more effectively. To date, no plausible mechanism describes this shift toward water wetness. Currently, this project area focuses on the formulation of a mechanism for a shift toward water wetness measured during previously reported high-pressure, high-temperature imbibition experiments in low permeability rocks (Tang and Kovscek, 2004). We have formulated a colloidal theory to explain the release of fine particles from porous media at elevated temperature. The release of fines from pore walls creates fresh water-wet surface because the grains underlying the fines were never contacted by asphaltenic crude oil that shifts wettability to mixed or oil-wet states. A step in the proof of this hypothesis is thus to show that high temperatures induce fines mobilization in porous media.

Results are still being gathered and a paper prepared for the Society of Petroleum Engineers International Thermal Operations and Heavy Oil Symposium and Western Regional Meeting (Schembre and Kovscek, 2004). Final results will be given in the Final Technical Progress Report.

Experimental

Experiments were designed to (a) validate the hypothesis that temperature is crucial in fines release and, (b) map the sensitivity of the conditions to the temperature. The rock samples are Berea sandstone (Cleveland Quarries). The advantages of using Berea sandstone include the considerable amount of clays and, its large permeability that allows experiments to be performed in a relatively short time.

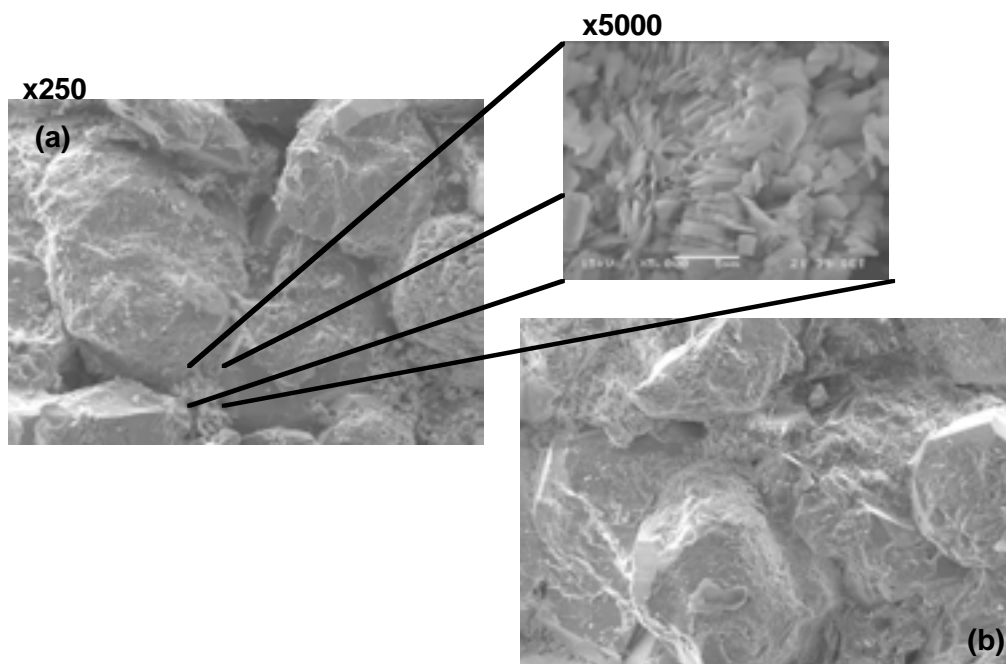


Figure 1. Scanning electron microscope images from the Berea sandstone core used in experiments: (a) before and, (b) after waterflood. Inset on (a) shows classical booklets of the clay kaolinite.

Figure 1 shows an image of the Berea Sandstone used, magnified at 250X with a scanning electron microscope (JEOL JSM-5600 LV). Note the fine material adhering to the sand grains. The area enclosed by the square was magnified 5000 times and it shows the classic plate-like or, accordion-like mineral form of kaolinite

We have performed 20 tests to date with unfired cores and 3 tests with a fired core. The cores were subject to single-phase water injection at different pH, salinity, and temperatures. The salinity and pH of each of the injection fluid is listed in Table 1.

Figure 2 shows the layout of experimental apparatus. The cores were cylindrical with length between 4 and 6 cm and diameter of 2.5cm. Core porosity ranged between 20 and 23 %. The apparatus is assembled by coating the core with a thin film of solvent resistant sealant (Fluoro Silicone Rubber) and placing the core inside FTP heat-shrink tubing (Plastic Professional). This covering serves as a high temperature sleeve. A net confining pressure of approximately 250–400 psia is applied.

The core holder is placed in the oven (Blue-M thermostated to $\pm 1^{\circ}\text{F}$) for waterflood at high temperature. Back- pressure is used in order to ensure single phase flow inside the core at high temperature. The pH of the solutions in all experiments was adjusted and controlled by using buffers. We used a buffer consisting of sodium hydroxide and potassium phosphate for pH 7. A solution of sodium bicarbonate and sodium carbonate was used for an alkaline pH of 10. Cores were flushed with a copious amount of buffer solution prior to temperature to satisfy any losses of buffer to the rock. The cores were subject to waterflood at different conditions. Corefloods were performed at constant Darcy velocity of approximately 1.0 m/day. This injection flow rate is typical for fluid injection and, small enough to prevent “wormholes” at high temperatures.

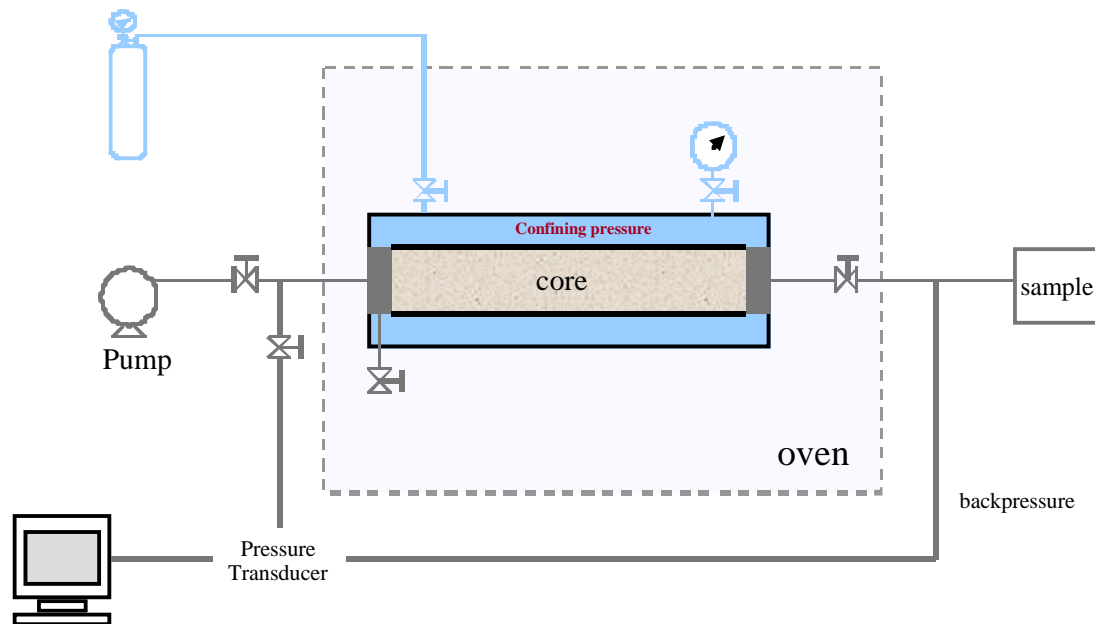


Figure 2. Schematic of the experimental setup used in the corefloods.

Results and Discussion

Figure 3 summarizes the experimental results and any damage of the porous medium resulting from high-temperature injection. It plots the reduction in permeability as a function of temperature. Open symbols denote that the core effluent is clear and free of fines. Closed symbols indicate that fines were produced. The initial permeability for all experiments was calculated at room temperature. After stabilizing flow, temperature was increased to 80°C (353 K), 120°C (353 K), and 180°C (453 K), sequentially. Permeability and fines release were monitored continuously. In all experiments, the cores that were not fired suffered reduction in the permeability as we increased the temperature. The permeability reduction might indicate the presence of swelling clays or that fine release occurs, but they do not mobilize. Nevertheless, the greatest reduction in permeability is associated with conditions that produce fines in the effluent. The experiments in fired cores showed little sensitivity to temperature and no fines production.

As reported in a prior Quarterly Technical Progress Report (Kovscek and Castanier, 2003b) elemental chromatography of the filtrate collected from the effluent confirmed that the fines produced are clay particles. Additionally, Fig 1 (b) presents a view of sandstone grains after thermal flooding we note the absence of any fine material on the grains

In earlier reports (Kovscek and Castanier, 2003a) we outlined colloidal attractive force calculations and a framework for predicting fines release as a function of temperature, salinity, and pH. In general the analysis predicts that fines such as kaolinite should release from silica surfaces under conditions typical of steam condensates such as pH of roughly 10, low salinity, and temperatures ranging from 150 to 200 °C. Figure 4 shows a contour map of the critical temperatures predicted by the colloidal theory. That is, the theory predicts that fines are mobilized at temperatures equal to exceeding those indicated on Fig. 4 for a particular salinity and pH. Overlain on the contour map are the experimental results. Each circle represents an experiment and each circle is shaded according to the temperature where fines mobilization was measured. Generally, excellent agreement is found.

Conclusions

This work is sufficiently complete that conclusions can be drawn. The interaction between fluid and surface forces is a dominant factor in wettability and formation damage. Interactions depend on factors including mineralogy of the porous medium, concentration and chemical composition of the fluids, pH, and temperature of the system. Temperature was very little studied in the past in relation to fines mobilization. In this work, we develop an understanding of fines mobilization through experiments and the role played by surface forces. Results confirm the decisive role of the interplay of temperature, pH, salinity, and mineralogy on these phenomena. The results presented here taught that temperature increase allows fine release under conditions of high pH and moderate salinity. Fines detachment changes the nature of fluid-solid interactions in porous media supporting our hypothesis that fines mobilization is a mechanism for porous media to shift towards water wetness during thermal recovery operations.

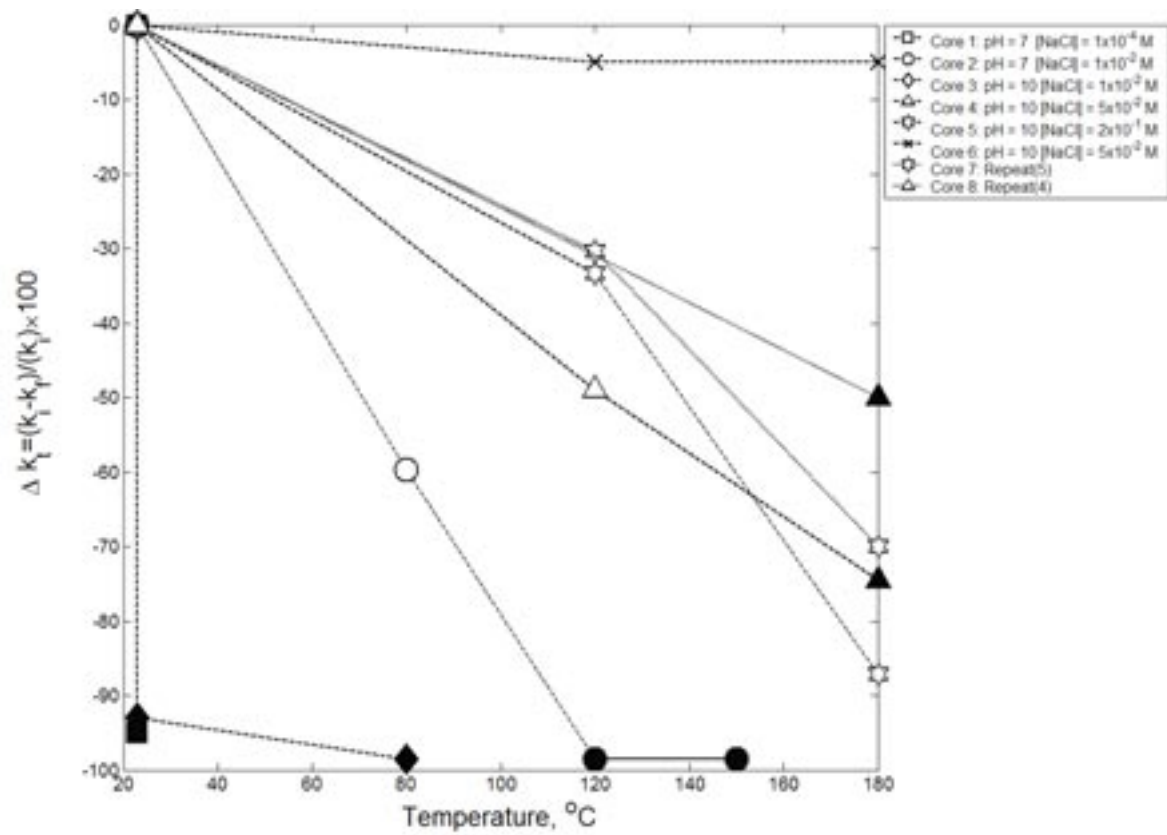


Figure 4. Permeability change during experiments. Open symbols: no-fines produced, closed symbols: fines produced.

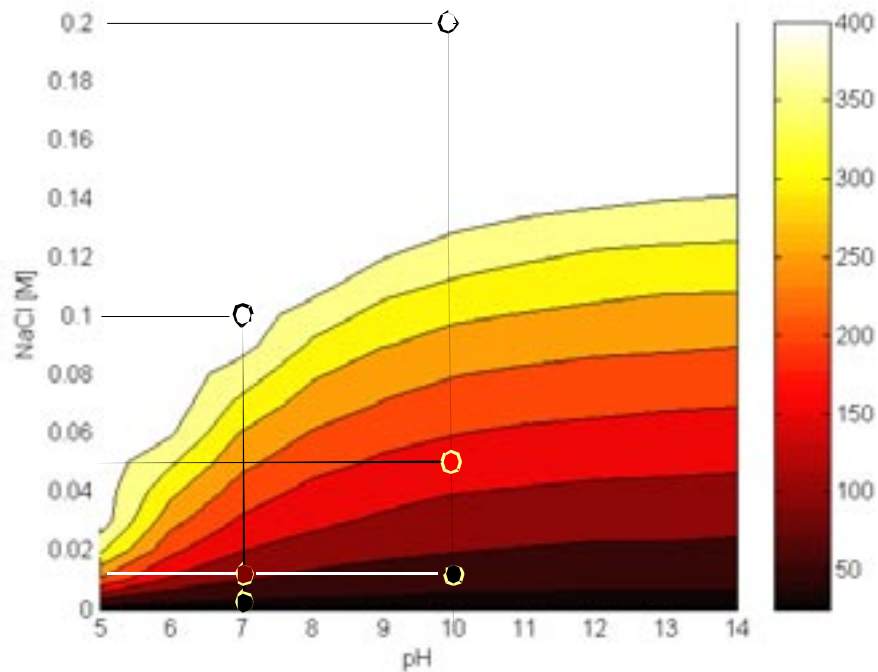


Figure 5. Detachment temperature obtained for quartz-kaolinite systems with ζ -potential measurements provided by Lorenz (1969). Shading is in degree Celsius ($^{\circ}\text{C}$). Circles represent experimental conditions.

Area 3. Mechanisms of Primary Heavy Oil Recovery

Tasks in this project area are complete with the exception of presentations at the Society of Petroleum Engineers Annual Technical Conference (Tang et al. 2003) and the International Thermal Operations and Heavy Oil Symposium and Western Regional Meeting (Tang et al., 2004). Final results will be given in the Final Technical Progress Report.

Area 4. In-Situ Combustion

Tasks in this area are complete. Final results will be given in the Final Technical Progress Report.

Area 5. Reservoir Definition.

Tasks in this area are complete. Final results will be given in the Final Technical Progress Report.

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List of Acronyms and Abbreviations

There are no acronyms of abbreviations employed.