CHARACTERIZATION and MODIFICATION of FLUID CONDUCTIVITY in
HETEROGENEOUS RESERVOIRS to IMPROVE SWEEP EFFICIENCY

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Principal Investigator: H. Scott Fogler

Project Manager: Robert E. Lemmon

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SUMMARY OF TECHNICAL PROGRESS

During the final quarter of this year, we have compiled all our research and written the final report. The primary focus of the work conducted was the development and study of new profile modification techniques. The following is a summary of our investigations into the fundamental aspects of each fluid diversion system.

The main objectives of this project were to develop new treatment strategies that would improve the efficiency of oil production, and stimulation procedures. Treatment strategies were developed to treat injection well matrix heterogeneities, production well matrix or saturation heterogeneities, and fractured wells. The treatment strategies investigated included a particulate system, and a foamed gel for injection well profile modification, a foam/acid injection strategy for improving acidization of carbonates, an acid reactive gel for controlling acid leak-off into fractures, and a water reactive gel for water shut-off at production wells. The research performed focused on discovering the principles governing the performance of the treatment strategies to provide a fundamental basis for further development of these techniques. Other goals of this project were to demonstrate the use of Neutron Imaging for real time imaging of fluid flow through heterogeneous porous media and develop a kinetic model to simulate the effect of diagenetic processes on reservoir porosity and permeability.

1. Injection Well Profile Modification

A foamed gel was studied for use as an injection well profile modification treatment. Advantages of foamed gel include: a controllable residual resistance factor, inhibited gel migration (slumping) after placement, and less chemical requirements than bulk gels. Visual experiments demonstrated that foamed gel efficiently plugs porous media

via the formation of gelled lenses in pore throat constrictions. The foamed gel filled region remained impermeable until pressure induced rupture of successive gelled lenses led to percolation of conductive channels. Although gel remained in the pore throats after rupture and hindered fluid flow, the foamed gel plug permeability increased as the conductive channel network increased in size. The percolation rupture pressure was found to depend upon the foamed gel quality, the gel strength and the permeability of the porous medium. These trends were supported by experiments which revealed a relationship between the rupture pressure of the individual gelled lenses and the ratio of the gelled lens length to the capillary constriction diameter. The foamed gel was proven effective for profile modification treatments on the laboratory scale.

The development of a model that simulates foamed gel breakdown hinged upon proper characterization of the gelled lenses in the pore space. In the interest of estimating the characteristics of a foamed gel (specifically location and number of gelled lenses) we have studied the formation of a foamed gel in porous media using glass micromodels of different pore configurations and two different types of gelling solutions. For long gelation times, the foamed gel consisted of one bubble in each pore body and one gelled lens in each pore throat. However, for short gelation times or high aspect ratio pore bodies, more than one bubble remained in each pore body.

The experimental studies provided the basis for development of a phenomenological model that simulates the breakdown of foamed gel. A network type model was utilized because of conceptual similarities with our experimental system as well as the ability to account for microscopic heterogeneities of foam and porous medium structure. The model determined foamed gel breakdown based on the deformation and subsequent rupture of gelled lenses. Experimentally determined relationships between gel properties and measurable parameters are used in the model. The model agreed qualitatively with trends found for foamed gel plugging macroscopically homogeneous pore spaces. With further refinement, the foamed gel breakdown model will be helpful in evaluating treatments on systems with matrix heterogeneities.

2. Acid Stimulation

Although acidization has been used for many years as a successful method for increasing the productivity of petroleum wells in carbonate formations, there are ever-increasing demands on the performance and application of the acidizing process. The present study investigated the use of foamed acid for stimulating carbonate formations. Foamed acid has potential to be used as a diverting agent as well as to increase the depth of acid penetration.

The goal of the experiments described in this report was to better understand the foamed acid diversion process, by studying the dissolution patterns in carbonate samples. The experiments were initiated by preflushing the carbonate core with an aqueous surfactant solution. Either nitrogen or a co-mingled acid was then injected to generate a foam. When stimulation was complete, the wormholes were characterized by Wood's metal castings and neutron radiographs. Parameters such as acid flow rate, gas flow rate, acid concentration, and the presence of foam were studied to determine their effect on the amount of acid required for wormhole breakthrough. Images of wormholes that were stimulated in the presence of foam are longer, thinner, and less branched. The reason for these structures can be understood from the fundamental concepts that describe pore-level dissolution, two-phase flow, and interfacial phenomena.

3. Water Control

As production wells age, and undergo secondary recovery, water production often becomes a problem. Not only is separation and disposal of produced water difficult, but acidizing these wells often results in stimulation of the water-bearing regions. Reactive diverting agents are designed to selectively plug watered-out zones, either for water-control purposes, or as acid preflush treatments. They are organic-based agents that form a gel or precipitate upon contact with water, and are meant to plug zones where this contact occurs, while leaving oil-producing zones undamaged.

Our study has shown that these diverting agents do not perform as they are ideally designed to work. Specifically, the permeability reduction that occurs in water-bearing zones is often not sufficient, and more importantly, damage is common in producing intervals. The reasons for the lack of selectivity are related first, to the organic nature of the diverting fluid, which displaces water away from the wellbore, and second, to the reaction of the diverting agent with low water saturations in oil-rich zones.

This project has defined what is required of the diverting agent, in terms of permeability reduction. More importantly, a simple method has been developed that provides a high degree of selectivity with slow-gelling reactants. This procedure, called the injection-backflow procedure, is a promising new technology to help control water production in the future.

4. Fluid Loss Control

Acid fracturing is a common production operation to increase drainage area of low permeability carbonate formations. In this process, acid etches surfaces of natural or artificial fractures to create conductive channels for flow. One of the factors which limits the success of this technique is excessive fluid leakoff due to channeling of the acid into the

formation. Acid leakoff cannot be controlled using methods designed to control fluid loss. Polymers which form gels in acid can theoretically control acid loss effectively. Such gels should be reversible to ensure that the formation is not damaged after the treatment. Sodium alginate is a commercial polysaccharide which exhibits acid gelling properties. The objective of this study is to evaluate the feasibility of using acid gelling polymers in permeability reduction and fluid loss control.

- A) Batch studies have demonstrated the reversible nature of the gel and the influence of mixing on the gel structure.
- B) Permeability modification has been realized in both high and low permeability cores, along with cores having significant permeability variations such as wormholes. In highly permeable cores, the mechanism of permeability reduction seems to be pore area reduction rather than pore blockage. The mechanism of permeability reduction in low permeability cores seems to be governed by size-exclusion.
- C) The effectiveness of the polymer in controlling non-reactive leakoff has been demonstrated using a hollow core reactor. The mechanism of leakoff control in this case seems to be either an external or an internal filtercake formation.
- D) Constant pressure acidization runs have demonstrated the effectiveness of the acid gelling polymer in delaying wormhole formation. This result demonstrates the feasibility of using such a model system in controlling reactive leakoff.

5. Modeling Particulate Injection for Injection Well Profile Modification

The efficiency of any flooding process depends on the number and type of different layers through which sweeping has to be accomplished. Matrix treatments are often performed to improve sweeping efficiencies in multi-layered formations which exhibit large differences in permeability. The various methods used to remedy this bypassing of the low permeability layers in heterogeneous strata include injection of particulate diverting agents, in-situ crosslinking polyacrylamide-chromium gel systems, lignosulfate gels, and alumina precipitates.

The success of these diverting methods depends to a large extent on the understanding of the fundamental mechanisms occurring in these systems. Phenomena

occurring in porous media have been modeled by various approaches including continuum, stochastic and network models. It has been demonstrated that network models can provide an understanding of the phenomena occurring at the pore scale and predict macroscopic changes with sufficient accuracy. The previous work involving network models have included only pore-scale heterogeneities. In this work, network modeling has been extended to simulate particulate flow in media with macroscopic heterogeneities.

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