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

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SUMMARY OF TECHNICAL PROGRESS

I. Introduction

A foamed gel is a dispersion of gas bubbles in a continuous gelled phase. Foamed gels are currently used for a wide variety of applications including fracturing oil-field reservoirs, stabilization of earthen formations, and plugging high permeability streaks (1-6). In these cases, foamed gel may be generated in situ, or externally prior to injection into the porous medium. The major difference between foamed gel and aqueous foam is that after some time, the external phase of the foamed gel crosslinks, greatly enhancing the stability as well as the mechanical strength of the foam system. This added stability improves the lifetime of the foam in fractures and prevents foam collapse during waterflood treatments as opposed to aqueous foams.

Successful application of a foamed gel system requires a well designed treatment based upon knowledge of the behavior of the foamed plug as well as the physical characteristics of the foamed gel in the pore space. In a recent study (performed under this grant), we have shown that foamed gels can plug porous media effectively and have also delineated the mechanism of fluid flow through the foamed gel, as well as the influences of the pertinent physical characteristics of the foamed gel and the porous media on the effectiveness of a foamed gel plug (7). The physical characteristics (quality, texture, location of gel) of a foamed gel after the external phase has gelled are particularly important because the location and amount of the gel at the pore level, and the bubble size will strongly influence the behavior of the foamed gel plug. There have been no studies reported that

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consider the physics of formation of a foamed gel and attempt to estimate the quality and texture of the aged foamed gel.

The objective of the experimental work performed this quarter, was to study one aspect of the formation of the foamed gel formed in a porous media. Specifically, the focus of the work was to investigate the change of foam texture and the configuration of the gelling phase during the gelation period.

II. Background

Changes in foam texture occur by two primary mechanisms: A) rupture of inter-bubble films, and B) inter-bubble diffusion between bubbles of different sizes (8, 9). Many factors lead to film rupture including poor stabilizing effect of surfactant, gravity drainage, pressure shocks, bubble rearrangement (10-12), and exceeding a limiting capillary pressure (13). Careful experimental design can eliminate these film rupture mechanisms. Disproportionation due to inter-bubble gas transfer cannot be eliminated in an aqueous foam. Disproportionation occurs because inter-bubble gas diffusion causes small bubbles to shrink progressively as their gas diffuses to larger bubbles. The cause of inter-bubble gas diffusion is due to the polydisperse nature of foam bubbles (causing gas pressure differences between different sized bubbles) and the high diffusivity of gas through the liquid films separating bubbles.

III. Experimental Apparatus

Etched glass micromodels were used to visualize the generation and subsequent disproportionation of the foamed gels. The general apparatus is depicted in Figure 1. A Harvard Apparatus model 22 syringe pump was used to meter the foaming solution into the porous system. Nitrogen gas was mixed with the foaming solution stream just ahead of the foam generator, or in the micromodel inlet if a foam generator was not used. The gas injection rate could be controlled using a mass flow controller, or adjusted to a constant pressure and monitored using a Brooks 5860E mass flow meter. The pressure at the inlet to the micromodel was measured using a Setra transducer. An Olympus SZ-11 stereo-zoom microscope equipped with a Panasonic Digital 5100 CCTV camera was used to magnify the micromodels for observation. The micromodel images were recorded using a Panasonic AG-7355 super VHS for further analysis.

Figure 1. Micromodel apparatus used for visualizing the formation of foamed gel.

Three micromodel pore configurations were used in this study. The first pore space configuration had square pore bodies connected together with pore throats in a square lattice arrangement (Figure 2a). These micromodels were used to observe the final configuration of the foamed gel in an interconnected pore space after gelation. The second micromodel pore space pattern consisted of one large channel (Figure 2b.). These micromodels were called "thin-cells". The thin-cells allowed us to observe the effect of foaming solution gelation on the evolution of the foam texture. They were designed to spread a pre-generated foam into a monolayer for easy characterization. Additionally, the length and width of the thin-cell were large enough that the growing bubbles would not be constrained by the boundaries of the system. The third micromodel pattern consisted of pore bodies connected in series by pore throats (Figure 2c, and 2d.). All pore bodies were connected by identical sized pore throats, and all pore bodies possessed the same etched volume. Two variations of this pattern were used. One pattern had square pore bodies ($L = 1.1W$), and the other had rectangular pore bodies ($L = 12.8W$) where L and W represent the length and width of the pore respectively. The purpose of these pore patterns was to study the influence of pore body geometry, in particular the aspect ratio of the pore body (L/W), on the texture of foamed gel.

Figure 2. Various micromodel patterns used in foam coalescence study. (not drawn to scale) a) portion of interconnected pattern, b) thin-cell, c) portion of $L/W = 1.1$ pattern, and d) portion of $L/W = 12.8$ pattern.

IV. Materials used in Foamed Gel Systems

Two types of foaming gel systems were used for this experimental investigation. One was a polyacrylamide gel system. Polyacrylamide from the Aldrich Chemical Company (approximate molecular weight 5 million Daltons and approximately 1% degree of hydrolysis), was mixed with de-ionized water and a cationic surfactant cetylpyridinium chloride (no interference with the polymer at a 10:1 polymer to surfactant weight ratio was observed). Chromium nitrate hydrate, $\text{Cr}(\text{NO}_3)_3 \cdot 9(\text{H}_2\text{O})$ was used as a crosslinker. By varying the concentration of polymer and crosslinker one can vary the gelation time and thus the diffusivity of the gas. The gelation time was defined as the time at which the gel will not flow out of an inverted beaker.

The other gel system used was a colloidal silica gel. A 3.5 weight percent sodium silicate solution with 2 weight percent of a non-ionic surfactant Polyterg SL-62 (Olin Chemical Co.) was mixed with a 50/50 mixture of de-ionized water and a 96 weight percent ethyl acetate, 4 weight percent formamide solution. The gelation time of the silica gel system could be varied by changing the ratio of the sodium silicate to ethyl acetate solutions mixed.

The purpose of using these two different gelling systems is as follows. The polyacrylamide gel formed elastic lenses when foamed, and the gelled lenses remained permeable to gas. In contrast, the silica gel formed rigid lenses after gelation and were much less permeable to gas. Hence, one could study the influence of the gelling characteristics on the evolution of foamed gel texture due to inter-bubble gas permeation.

V. Experimental Summary

Our experimental findings are summarized as follows,

- 1) Foam injected into a porous medium, such as glass micromodels, will undergo disproportionation via gas bubble diffusion until an equilibrium state is achieved for disproportionation dominated foams. The equilibrium state will be one bubble per pore body and one lens per pore throat when the pore body length to width ratio is small (see Figure 3).

Figure 3. Effect of the pore aspect ratio on the evolution of foam texture.

- 2) Rapid formation of a gas impermeable gel (gelation dominated) and/or high aspect ratio pores will preserve foam texture (see Figure 4).

Figure 4. Evolution of foam texture of a foamed silica gel at different gelation times.

The experimental study underscores the factors which govern the texture of foamed gel in porous media. In a medium where the pore body length to width ratio is close to 1 (sandstone, sintered porous materials, compacted soil) the disproportionation of foam will stop when the bubbles grow to the size of the pores or when the external phase of a gelation dominated foam gels. In porous media with a large pore body length to width ratio (fracture networks) the disproportionation is limited by the aspect ratio of the fracture as well as the gelation of the external phase.

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