Surfactant-Enhanced Steam Drives for Heavy Oil Recovery

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ABSTRACT

A steam/noncondensible gas foam formulation was developed to reduce steam mobility in the steam drive process as applied to heavy oil reservoirs with little or no dip such as the Kern River field. The steam/noncondensible gas foam process is intended to reduce or minimize the gravity layover problem in such reservoirs. Laboratory experimentation started with foam studies in the absence of both porous media and crude oil at a substeam temperature. Conditions existing in the application under actual field use were then added in a step-by-step manner, i.e., inclusion of porous media, existence of an oil saturation, and the addition of steam foam components to injected steam. Added salt was necessary for mobility reduction. Mode of noncondensible gas injection (constant mass vs constant volume) was not important. Adsorption of surfactant was shown to be quite low at steam temperature. The concentrations of steam foam components – Siponate DS-10, salt and nitrogen – recommended for the Kern River pilot resulted in a steam mobility 0.18 of that obtained with steam alone.

INTRODUCTION

This report describes laboratory work in the development of a steam foam formulation initially tested at the Mecca lease of the Kern River field for a five-month period in 1976-77. The Mecca lease had been under conventional steam drive since 1970. As is typical for heavy oil reservoirs with little or no dip, oil production response is impaired by gravity overlay of the steam. Injected steam rises to the top of the reservoir, and once breakthrough occurs, little pressure differential is realized between injector and producer due to high steam mobility.

One mechanism for decreasing steam mobility, and thereby increasing the pressure gradient from injector to producer, is to have the steam present as a portion of the gas phase of a foam. The surfactant system initially studied was that developed for well clean-out with steam foam: a combination of Siponate DS-10 and Neodol® 25-3S (1). Foam stabilities were studied at both substeam and steam temperatures in an all-glass apparatus in the absence of both porous media and crude oil; mechanisms of foam collapse were determined under these conditions (2). The same surfactant was used to generate foams at both substeam and steam temperatures in Ottawa sand packs of average Kern River permeability. Porous media were found to stabilize substeam temperature foam to a significant degree. The debilitating effect of Kern River crude oil on steam foam was examined. It was learned that the Neodol® 25-3S could be omitted from the steam foam surfactant system, provided that ionic strength is maintained through the addition of salt. The cases of constant mass vs constant volume of noncondensible gas injection modes were ascertained. Adsorption of Siponate DS-10 on Kern River reservoir rock at steam temperature was shown to be quite low.

The steam foam formulation recommended for testing in a single-pattern pilot at Kern River Mecca lease contained 0.5% wt Siponate DS-10 and 1.0% wt NaCl in the liquid phase of the injected foam and a mole fraction of 0.006 noncondensible gas (nitrogen) in the gas phase of the foam. This results in a steam mobility reduction to 0.18 of the case for steam-only injection.

DISCUSSION

Steam Drive and Gravity Layover

Application of thermal recovery techniques to heavy oil reservoirs is the most commercially successful enhanced oil recovery (EOR) method at this time. Both steam soaks and steam drives are used. More recently, however, steam drives have been emphasized because of their higher ultimate recovery.

A significant problem exists with the application of the steam drive process to reservoirs with little or no dip, however. This problem is illustrated in Figure 1 and is known as gravity layover. Injected steam, because of its low density, rises to the top of the reservoir and tends to form a channel beneath the cap rock to the production well. Once steam

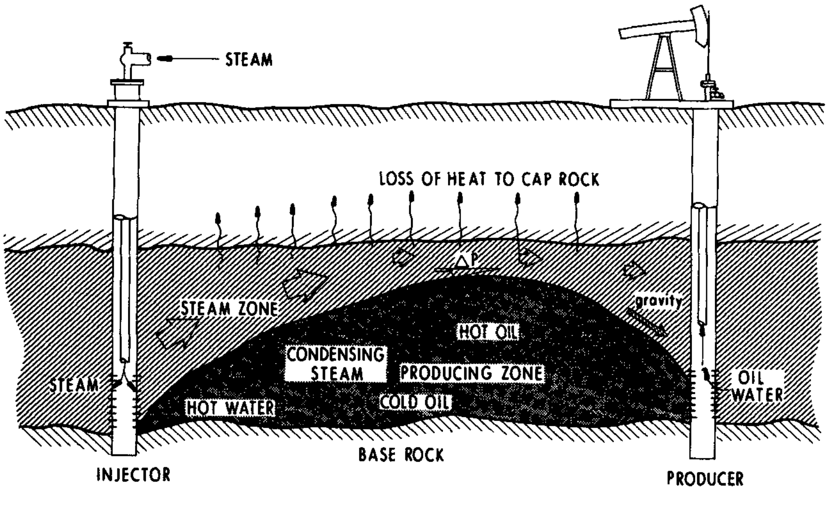


FIG. 1. The steam drive process.

breakthrough occurs at the production well, there is little pressure differential between injector and producer to move the oil because of high steam mobility. The majority of subsequently injected steam follows this established path of least resistance and process efficiency is impaired.

The gravity layover problem exists at Shell's Kern River field, Mecca lease, steam drive pilot. The pilot is composed of four contiguous 2.5-acre five-spots. Net pay is about 50 ft. The reservoir dips 3½ degrees to the southwest (Fig. 2). The steam drive was initiated in 1970 and, by 1976, the injected steam had swept out the top ca. 20% of the interval. The work described in this report was aimed specifically at improving the process efficiency of the steam drive at Kern River.

Improved Steam Drives via Steam Foam

One mechanism for decreasing steam mobility is to have steam present as a portion of the gas phase of a foam. Reduced steam mobility would result in higher pressure gradients between injector and producer, thus moving more of the hot, mobile oil. Both vertical and areal sweep efficiency should be improved (3). The idea of steam foam having actual mechanical strength is not new to Shell research. Indeed, in the early 1970s, a steam foam formulation was developed by Smith et al (1) for well clean-out and was successfully tested in the Midway-Sunset field. In this application, steam foam was used to lift substantial quantities of rock fill and debris from wellbores. Smith et al. discovered that it was necessary to include some noncondensible gas in the steam foam formulation to attain mechanical strength. They further noted that a foam prepared from a pure liquid and its own vapor (e.g., liquid water, steam and surfactant) is thermodynamically unstable.

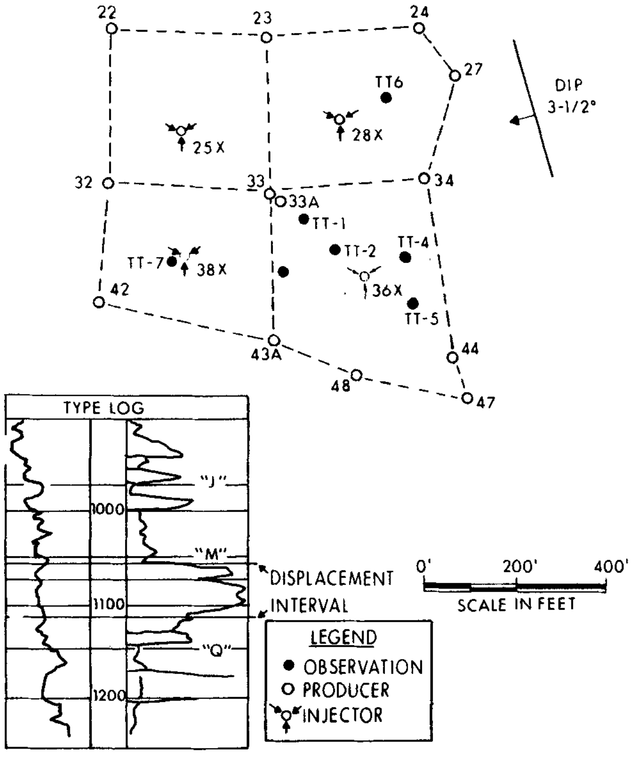


FIG. 2. Kern Field, Mecca lease steam drive.

Experimental Approach Used in the Development of Steam/Noncondensible Gas Foam

The sequence of experimental events leading to the recommendation of a steam/noncondensible gas foam formulation for Kern River is summarized in Figure 3. After selection of an initial surfactant system, foam stability was studied at a substeam temperature outside of a porous media and in the absence of oil. Increasing degrees of complication were then introduced one at a time until finally steam/noncondensible gas foam process parameters were examined in porous media in the presence of Kern River crude oil. At the time this work was undertaken, steam foam documentation in the literature was conspicuous by its absence. An exception was the patent literature which, however, recorded neither hard experimental data nor examples of real-world field application (4).

Selection of Initial Surfactant System

The surfactant system selected for initial study was that developed by Smith et al. (1). It is an aqueous solution of Siponate DS-10 and Neodol® 25-3S in a 2:1 wt ratio. This system was chosen for its excellent foaming characteristics and its relative compatibility with crude oil, multivalent ions and reservoir minerals. The chemical structures for these two commercially available surfactants are shown in Figure 4.

Noncondensible Gas Foam Stability

Examination of the rates of foam collapse gives an indication of the mechanism(s) of foam degradation (2). If gas diffusion from the smaller to larger bubbles is the predominating decay mechanism, zero-order kinetics should be displayed. Thus V_t, the volume of foam remaining at time t should be linear with time (Fig. 5a). If drainage of the liquid phase between the gas bubbles and/or statistical rupture of the liquid films separating the bubbles are responsible for foam decay, then first-order kinetics should obtain—V_t will be an exponential function with respect to time and log V_t will be linear with time (Fig. 5b). A third commonly observed mode of foam collapse has been termed "cata-

Selection of surfactant system
↓
Noncondensible gas foam stability at substeam temperature
(no steam, no porous medium, no oil)
↓
Steam foam stability
(no porous medium, no oil)
↓
Noncondensible gas foam in porous medium at substeam temperature
(no steam, no oil)
↓
Steam foam in porous medium
(no oil)
↓
"Simplification" of surfactant system
↓
Steam foam in porous medium in the presence of oil
↓
Mode of noncondensible gas injection
(constant mass vs constant volume)
↓
Effect of NaCl concentration
↓
Adsorption studies on Kern River reservoir rock
↓
Field test at Kern River field

FIG. 3. Methodology used in the development of steam foam.

cylsmic" collapse (see Fig. 5c). Volume measurements under this circumstance are impossible to obtain.

An all-glass apparatus was designed and constructed for the quantitative measurement of foam stability outside of porous media. The apparatus is essentially a foam tube in which a quantity of foam is generated and then allowed to go static. The rate of foam collapse is then observed. Foam stability measurements were conducted at 180 F (80 C). The aqueous surfactant solution was 1.0% wt Siponate DS-10/Neodol® 25-3S (2/1:wt/wt). Foam quality, i.e., the volume fraction in the gas phase, was 90%. The noncondensible gas was nitrogen. Data for the degradation of this foam are summarized in Figure 6. In this figure, the same experimental data are given the zero-order kinetic treatment (lower curve, left-hand scale) and first-order treatment (upper curve, right-hand scale). Examination of Figure 6 leads to the following picture of foam collapse. It appears that first-order kinetics apply during the early stages of foam collapse–i.e., liquid drainage is the primary mechanism of degradation. When the foam is for the most part drained (note marker on the abscissa), zero-order kinetics take over–diffusion of gas from smaller to larger bubbles is the predominant degradation mechanism. Indeed, this is what is visually observed during the latter stage of foam decay–some of the bubbles attain diameters of 1-2 cm before bursting. Note that the foam collapsed completely in a little over 6 min.

Steam/Noncondensible Gas Foam Stability

The same surfactant system was used to prepare a foam at the boiling point of water (atmospheric pressure). The gas phase of the foam was 90% steam and 10% nitrogen. Foam quality was again 90%. The results are shown in Figure 7. Here, one is unable to say which kinetic order predominates in the early stages of foam degradation; the early data points seem to fit both kinetic orders equally well. Visually, we know this foam drains very rapidly (less than 5 sec), so perhaps the simplest description is also the best description: gas diffusion is the predominant mechanism of foam decay thoughout the life of this foam. This is consistent with what is observed visually, i.e., the larger bubbles grow at the expense of small bubbles.

Flow Experiment in Porous Medium at Substeam Temperature

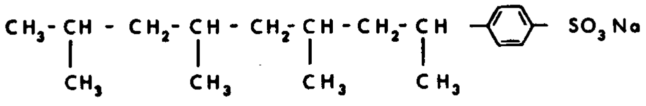
The same foam system studied in the all-glass apparatus at 180 F (80 C) (Fig. 6) was examined in a porous medium. The apparatus was an Ottawa sand pack, 12 in. in length and 1.54 in. in diameter. Permeability was 4 darcies, porosity was 34% and the pore volume was 125 mL. The pack was equipped with a pressure tap at the inlet and two interior taps spaced at 1/3 and 2/3 of the distance along the pack. The sand pack was mounted vertically in a flow oven at 180 F (80 C). No oil was present. The Siponate DS-10/Neodol® 25-3S foam studied in the all-glass apparatus (Fig. 6) was injected from bottom to top until steady-state pressures were observed at the inlet as well as the interior taps. The mode of noncondensible gas injection was constant volume. At steady state, the ratio of the permeability in the presence of foam to that in the absence of foam was 10^{-3}, reflecting mobility reduction due to the presence of foam. An interesting feature of this experiment was that a 50-psi pressure difference remained across the two interior taps 16 hr after the experiment was ended and injection of foam components was discontinued. Note that the same foam collapsed completely after 6 min in the all-glass apparatus. Thus, the porous medium apparently increased the collapse time of the foam.

Flow Experiment in Porous Medium with Steam Foam

The next step was to study steam mobility reduction due to foam. Again, a 1-ft long, 4-darcy Ottawa sand pack was used with no oil present. The composition of the injected steam foam was the same as that studied in Figure 7. Fifty percent quality steam and foam components were injected (the nitrogen on a constant volume basis) until steady-state pressures were observed. The term "quality" as applied to steam refers to the mass fraction in the gas phase.) At steady state, the ratio of the permeability in the presence of foam to the permeability in the absence of foam was 5×10^{-2}.

"Simplification" of Surfactant System in Flow Experiment in Porous Medium with Steam Foam

Neodol® 25-3S was included inthe well clean-out formulation to provide divalent ion tolerance. The connate water in th Kern River field, however, is relatively soft–calcium ion concentrations are in the range of only 40-60 ppm. This raised the question of whether Neodol® 25-3S were necessary for a steam foam formulation aimed at the Kern River field. To answer this question, the experiment described in the preceding section was repeated except that the sand



SIPONATE DS-10

$CH_3(CH_2)_{11}-(OCH_2CH_2)_3-OSO_3Na$

THROUGH

$CH_3(CH_2)_{14}-(OCH_2CH_2)_3-OSO_3Na$

NEODOL 25–3S

FIG. 4. Steam foam surfactant system for well clean-out. Siponate DS-10:Neodol® 25-3S::2:1 (wt/wt).

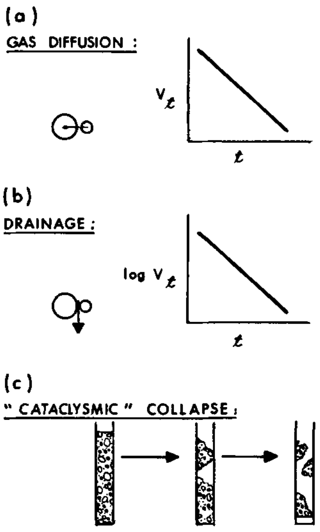


FIG. 5. Kinetics of foam column collapse are indicative of collapse mechanism.

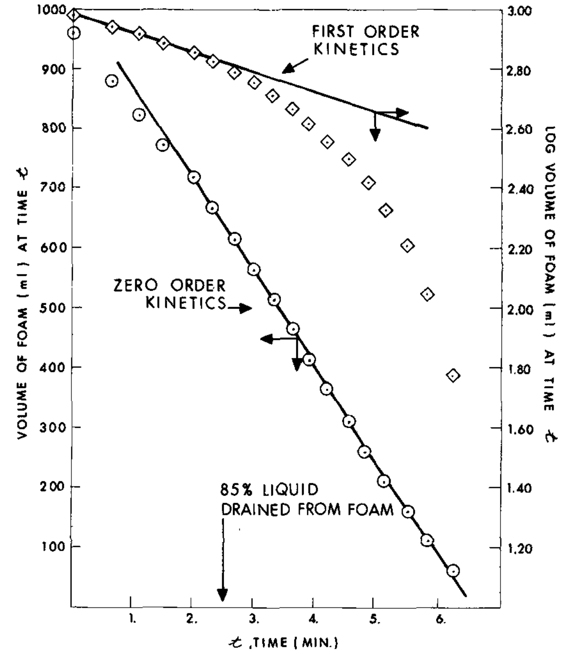


FIG. 6. Application of zero and first-order kinetics to the degradation of foam prepared from 1% wt (Siponate DS-10:Neodol® 25-3S::2:1) in H_2O and nitrogen at 180 F.

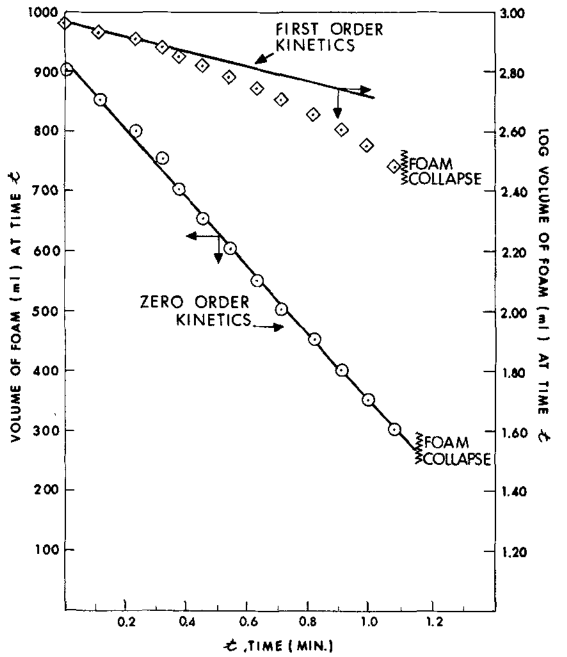


FIG. 7. Application of zero and first-order kinetics to the degradation of foam prepared from 1% wt (Siponate DS-10:Neodol® 25-3S::2:1) in H_2O and steam plus nitrogen at 212 F (100 C). Steam: Nitrogen::90:10 (v/v).

pack was prepared in KErn River produced water. The Neodol® 25-3S was omitted and 1.0% wt NaCl (for ionic strength) was included in the liquid phase of the injected steam foam. No oil was present. The steady-state permeability reduction was comparable to that attained when the Neodol® 25-3S was included. This was a favorable result, as it islikely that Neodol® 25-3S, like other sulfate surfactants, would hydrolyze under the temperature ranges and time spans encountered in the steam drive process.

Flow Experiment in Porous Medium with Steam Foam in the Presence of Residual Oil

A Kern River crude oil saturation of 30% pore volume was established in the 1-ft long, 4-darcy sand pack. The permeability to steam at this oil saturation was measured in the absence of foam. Steam foam components were then injected in the 50% quality steam. Siponate DS-10 and NaCl concentrations in the liquid phase of the foam were 0.5% and 1.0% wt, respectively. Initial mole fraction of nitrogen (constant volume injection mode) was 0.006; at steady state, the mole fraction was 0.030. Upon achieving steady state, the ratio of the permeability in the presence of foam to the permeability in the absence of foam was 0.12.

Mode of Noncondensible Gas Injection: Constant Mass vs Constant Volume

The steam foam drive experiments described above used a constant volume injection mode for noncondensible gas (nitrogen). Consideration of conditions in the field, i.e., lack of prior knowledge of flowing bottom-hole pressure response to steam foam in the injector, suggested that a more prudent course would be constant mass nitrogen injection in order to manage better the nitrogen usage. An experiment was performed exactly as in the preceding section except that the mole fraction of nitrogen was maintained at 0.006 in the gas phase of the foam throughout the course of the experiment. At steady state, the ratio of the permeability in the presence of foam to the permeability in the absence of foam was 0.18. This particular foam formultion with constant mass nitrogen injection was that selected for initial field testing in the Kern River field. Later field testing used α-olefin sodium sulfonates, both branched and linear. The α-olefin sulfonates appeared to be more cost-effective than the alkylbenezene sulfonates. Results of this initial and subsequent field testing are discussed elsewhere (3,5).

Effect of NaCl Concentration

The steam foam formulation proposed for the Kern River field test used 0.5% wt Siponate DS-10 and 1.0% wt NaCl in the liquid phase of the 50% quality steam and nitrogen mole fraction of 0.006 in the gas phase of the foam. Additional experiments were performed to examine the effects of lower (zero) and higher (3.0% wt) NaCl concentrations on steam foam strength. Results are summarized in Table I. The results indicate that added NaCl is necessary for an effective steam foam, though 3.0% wt NaCl is only marginally better than 1.0% wt NaCl.

TABLE I

Effect of NaCl Concentration on Steam Foam Strength

NaCl concentration in liquid phase of injected foam (%wt)[a]	Permeability to steam in the presence of foam/permeability to steam in the absence of foam
0.0	1.0
1.0	0.18
3.0	0.15

[a] Surfactant system 0.5% wt Siponate DS-10; mole fraction nitrogen = 0.006; steam quality 50%.

Adsorption Aspects of the Steam Foam Process

Extent and nature of adsorptive loss to reservoir rock is an important process and economic parameter in any flooding process using surfactants. Therefore, a brief investigation was made of the adsorption of Siponate DS-10 on Kern River reservoir rock at temperatures ranging from near room temperature to steam temperature at atmospheric pressure. The surfactant will encounter at least this approximate temperature range if the steam foam effectively reduces flow in the already steamed-out zone. Changes in level of adsorption with temperature, moreover, are indicative of mechanism of adsorption and suggest whether adsorption is reversible or irreversible (6).

The Kern River reservoir rock studied was taken from an observation well drilled at the site of the steam drive pilot. Upon extraction of oil and water from the core, the rock became disaggregated. Particle size ranged from ca. 5 mm down to fine dust. Feldspar and quartz are the principal components. A detailed analysis and surface area are shown in Table II.

Portions of isotherms for adsorption of Siponate DS-10 in 1.0% wt aqueous NaCl on Kern River reservoir rock were determined at 30, 50 and 100 C. The results are shown raphically in Figure 8. The range of initial surfactant concentrations studied cover that which would probably be used in the field (i.e., low–0.5% wt); hence, only the ascending portions of the isotherms were obtained. Adsorption decreases from high levels at room temperature to low levels at steam temperature. The important point is that adsorption of Siponate DS-10 on Kern River reservoir rock decreases with increasing temperature over the entire temperature range studied–this is consistent with reversible physical adsorption (6).

TABLE II

Surface Area and Estimated Weight Percent Crystalline Components in Crystalline Portion of Mineral Used in Adsorption Experiments

	Kern River reservoir rock
Surface area (m^2/g)	2.2
Crystalline components (%)	
Quartz	45
Feldspar	50
Clay	5
Clay fraction <2 μ (clay only)	
Kaolinite	10
Illite	50
Montmorillonite	40

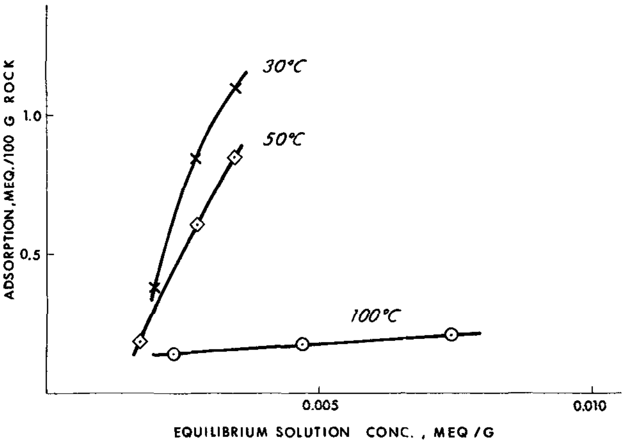


FIG. 8. Adsorption isotherms of Siponate DS-10 in 1% aqueous NaCl on Kern River reservoir rock at 30, 50 and 100 C.

ACKNOWLEDGMENT

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