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STUDY OF EMULSION TECHNOLOGY FOR IMPROVING GAS SWEEP EFFICIENCY

Project BE5B, FY89 Annual Research Plan, Milestone 5

by Frank Chung

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ABSTRACT

The possibility of emulsion generation in a CO_2-alternating-surfactant solution injection process and the application of emulsions for gas mobility control and sweep efficiency improvement were investigated in this project.

Stable emulsions of both oil-in-water and water-in-oil types can be generated by injecting oil and surfactant solutions alternatively into a core. The generated emulsions can significantly reduce the permeability of the core. The concept of emulsion droplet blockage, which has been considered to be the mechanism for permeability reduction, has been found to be inadequate. Instead, adsorption and accumulation of emulsion particles inside pore spaces are believed to be the major mechanisms for permeability reduction. Coreflooding tests have shown the effectiveness of alternating injections of emulsion slugs in CO_2 floods for delaying gas breakthrough. The effectiveness of emulsions for improving gas sweep efficiency in profile modification, which depends on many factors such as formation heterogeneity, injection rate, and multiphase flow phenomena remains as an unproven technique.

INTRODUCTION

A water-alternating-gas (WAG) injection strategy is commonly used to mitigate the effects of an unfavorable mobility ratio. The addition of low concentrations of surfactant to the water cycle of the WAG process has been used to generate foams or dispersions that help to improve gas sweep efficiency. Most research has focused on foam technology for gas mobility control. However, the stability of foams in contact with crude oils is questionable, and it is known that high oil saturation can be detrimental to foam generation. Emulsions or dispersions can be generated with the addition of a surfactant to brine slugs in the WAG process. A surfactant in the brine cycle may affect both oil displacement efficiency and sweep efficiency by generating macroemulsions. The large solubilization of oil in an aqueous medium and very low interfacial tensions that can be achieved between the macroemulsion and an oil or water phase may contribute to oil recovery. An oil-in brine emulsion phase may block high-permeability zones and reduce gas channeling.[1] Research has been conducted to use emulsions for sweep improvement in waterflooding and steamflooding;[2-4] however, no study on applications of emulsions in gas flooding has been found in the literature. The mechanisms of macroemulsion generation and the effect on local displacement efficiency and gas sweep efficiency are not well understood. The objective of this study is to determine the mechanisms of emulsion generation and their effects on both local displacement efficiency and gas sweep efficiency.

McAuliffe[1] found that oil-in-water emulsions can be easily prepared from some asphaltic crude oils and dilute solutions of sodium hydroxide. Crude oils that do not contain enough organic acids to produce emulsification upon the addition of sodium hydroxide can be emulsified by adding a synthetic surfactant. There are two types of emulsion systems: oil-in-water and water-in-oil. Emulsions are usually classified as microemulsions and macroemulsions, depending on the droplet size (as shown in figure 1).[5] Macroemulsions have droplets whose diameters, in general, exceed 0.1 micron. Microemulsions are of smaller droplet size (0.01~ 0.1 micron) and are optically transparent. Emulsion droplet sizes and size distributions vary with oils and are also dependent on the concentration of emulsifying agents and preparation methods. Emulsions with droplet diameters larger than the pore throat would give the greatest restriction to fluid flow. The flow properties of oil-in-water emulsions in porous media have been investigated.[1-4, 6-7] The concept of the plugging of pore constrictions by individual oil droplets, as proposed by McAuliffe, has been commonly accepted as the major mechanism for emulsion blockage. However, there are some discrepancies among published results, and some conclusions are controversial. These points will be discussed in the following sections.

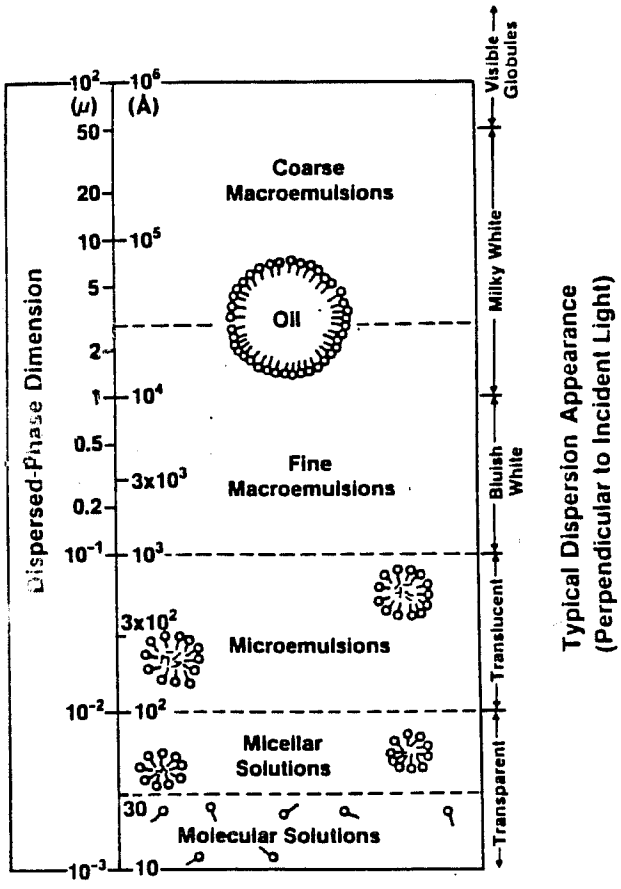


FIGURE 1. - Dimensions of dispersed phase for liquid-liquid dispersion (from ref. 5).

This study has been focused on emulsion generation caused by the injection of a low-concentration foaming agent in the WAG process and the effect of emulsion on permeability. The foaming agent being used in this study is Alipal CD-128 produced by GAF Chemical Company. Alipal CD-128 is an anionic surfactant of sulfate-ester-type, which is soluble and stable in highly concentrated electrolyte solutions. The surfactant solution used is a 1 wt % active surfactant in 5 wt % NaCl solution. This surfactant solution has been tested and proven to be a good foamer with N_2 or CO_2 at high temperatures and pressures.[8] Also, data about the foaming properties of Alipal CD-128 are available in the literature. It is not the purpose of this work to make any comparison or screening among different surfactants. The same surfactant solution and oil are being used throughout this study. The oil used in this study is an oil of 22.7° API gravity, obtained from Bloomington (TX) oil field, which has been used in previous CO_2-flooding studies. The viscosity and density of the sample oil is about 18 cP and 0.918 g/cm^3 at room temperature, respectively.

EMULSION GENERATION

Crude oils can be emulsified by agitating or shaking oil with an emulsifier solution.[9] The types and properties of the generated emulsion depend on the oil, the emulsifier, and the emulsification process. Most of the published studies have used heavy oils with viscosities greater than 1,000 cP. They all dealt with only oil-in-water(O/W) type emulsions; however, in these shake tests, the generated emulsions were encompassed in the water films among gas bubbles. The generated emulsions are more stable with light oils than with heavy oils. As shown in a microscopic view of the emulsion (fig. 2), many gas bubbles (large bubbles) were stably dispersed with emulsion droplets (small diameter). Temperature has a significant effect on the stability of the generated emulsion. This milky emulsion is very viscous and behaves as a non-Newtonian fluid (see Fig. 6).

To investigate the possibility of emulsion formation in situ during the WAG process with the addition of a surfactant in water slugs, the surfactant solution and the sample oil were injected alternatively into a brine-saturated Berea core at 50 cm^3/hr. Both types of emulsions, O/W and W/O, were produced by this process. Figure 3 shows the produced emulsions. The upper part, with brown color, is a W/O emulsion; the lower light-brown part is an O/W emulsion. The type of emulsions can be easily identified by the appearance of the emulsion or by diluting with water. Both types of emulsions were stable, even at high temperatures (no separation at 212° F). The O/W emulsions are considered to be generated by the snap-off of oil droplets into the surfactant solution phase during flow in a porous medium. Oppositely, the W/O emulsions were probably generated by the mixing of water and oil inside the porous medium. This was shown by the alternating production of the two types of emulsions in the oil-alternating-surfactant solution injection

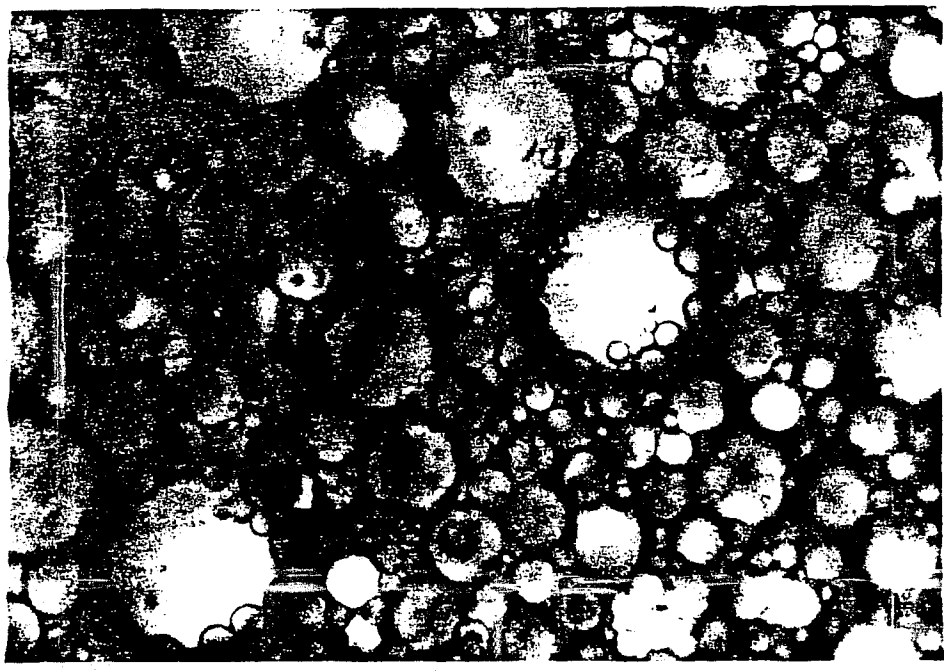


FIGURE 2. - Emulsions generated by shaking oil with surfactant solution (400x).

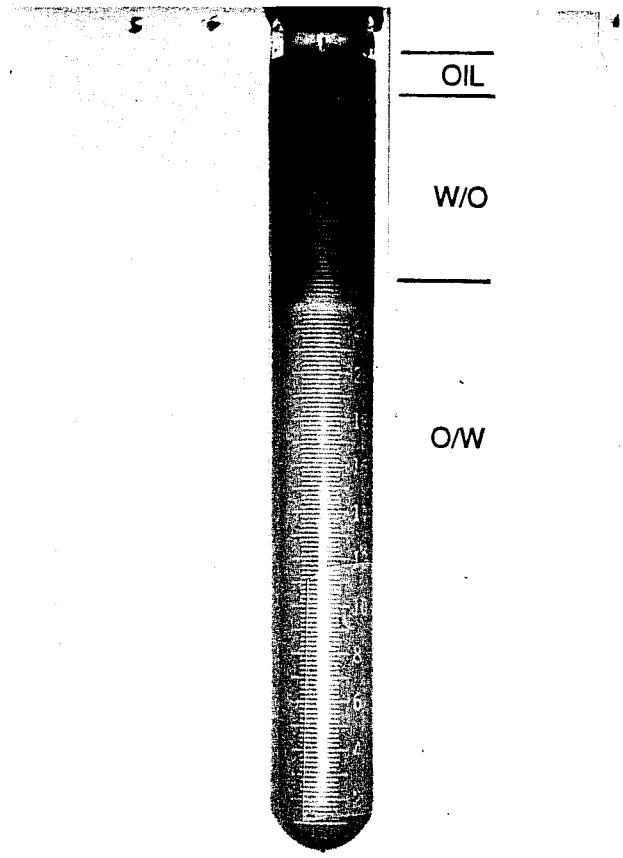


FIGURE 3. - Emulsions generated from a core by oil-alternating-surfactant solution injection.

process. The experiments also show that emulsions can be formed in situ when the injected surfactant solution contacts the oil in reservoir formations.

EMULSION PROPERTIES

The two types of emulsions have different properties. As shown in figure 3, the W/O emulsion is less dense than the O/W emulsion which is close to the density of brine (oil specific gravity = 0.918). After settling for a period of time, the bottom part of the test tube became more transparent. Larger oil droplets floated and accumulated at the upper portion. There was no significant gravity segregation in the W/O portion due to its high viscosity. Droplet size distributions for O/W emulsions (fig. 4) were determined with a Model TA II Coulter counter. Within the limitations of this instrument, we were unable to determine the droplet size distributions for the W/O emulsion. The droplet sizes for the O/W emulsions range from about 0.3 to 3.5 μ, with an average diameter of 1 μ. The size distribution of emulsion droplets is related to the pore size distribution of the core used to generate the emulsion and the flow rate.

The oil content, determined by the dilution with methanol (fig. 5) is about 12% for O/W emulsions and about 80% for W/O emulsions. The properties of the emulsions and other fluids are listed in table 1. Thus, O/W emulsions tend to have the viscosity of the continuous phase (surfactant solution). But, W/O emulsions have higher viscosity than that of oil and have non-Newtonian behavior at lower shear rate (shear thinning behavior) (fig. 6).

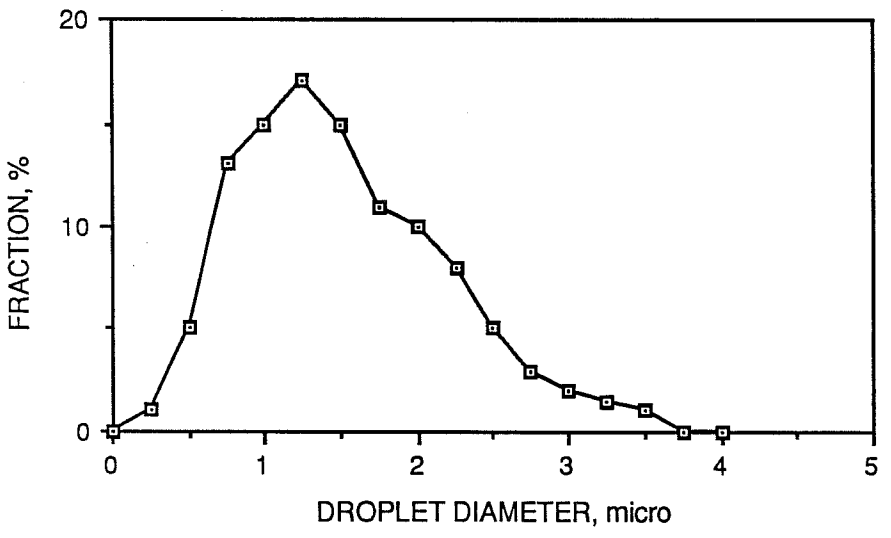
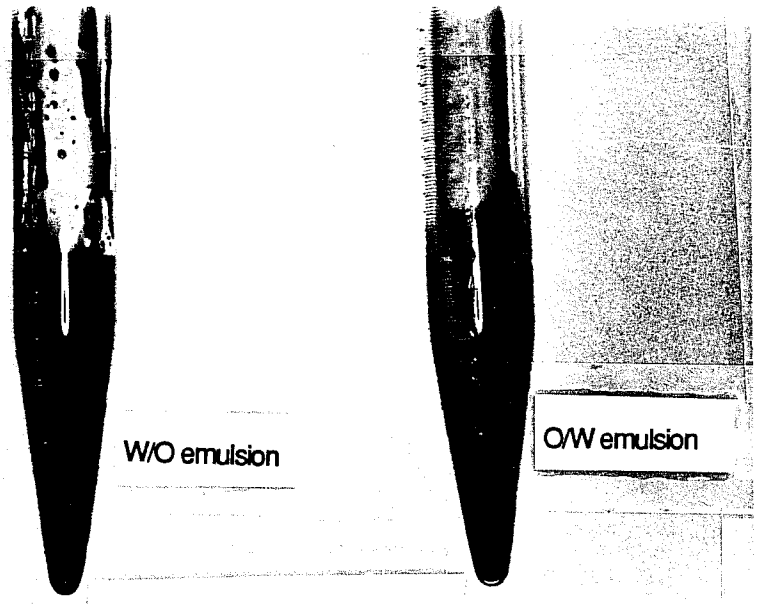
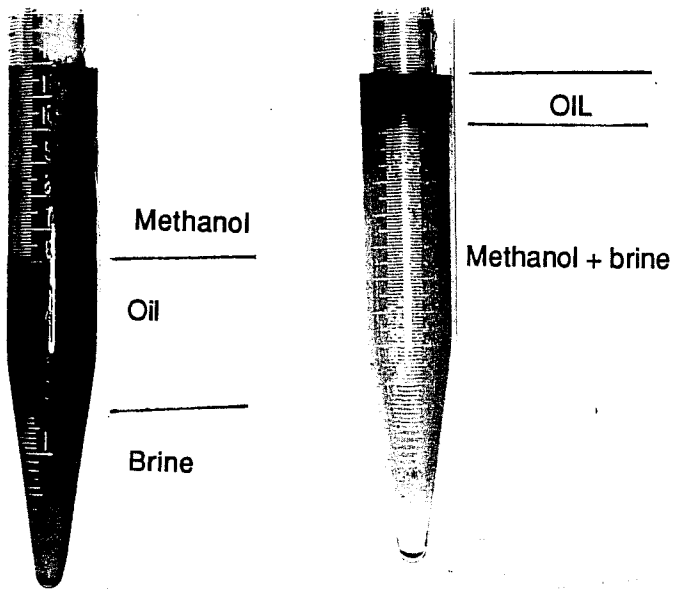


FIGURE 4. - Droplet size distribution of the oil-in-water emulsion.



(a) Original emulsions



(b) Diluted with methanol

FIGURE 5. - Results of dilution with methanol for both O/W and W/O emulsions.

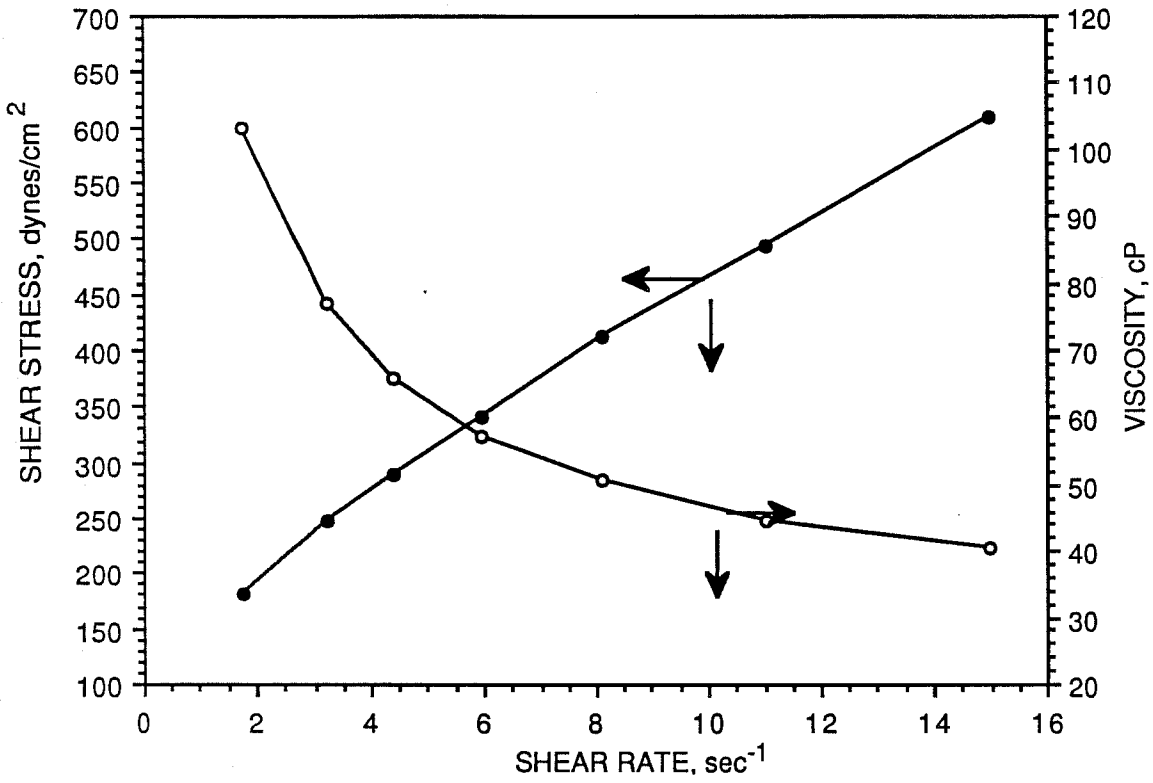


FIGURE 6. - Viscosity and shear stress of W/O emulsion vs. stress rate.

TABLE 1. - Properties of fluids

Fluid	Viscosity, cP	Liquid-air surface tension, dynes/cm
Oil (22.7° API)	18.8	29.8
Brine (5 wt % NaCl)	1.09	69.2
Surfactant-brine solution (1 wt % active Alipal CD-128)	1.18	28.5
Emulsions:		
Water-in-oil	(see fig. 6)	30.0
Oil-in-water	1.45	28.5

IFT of oil/brine = 8 dynes/cm, oil/surfactant solution = 1.9 dynes/cm.

EMULSION BLOCKING MECHANISMS

The O/W emulsion is a two-phase system. The oil droplets are homogeneously dispersed in the water phase. Injecting the emulsions into porous media will create numerous oil-water interfaces within a short length. Thus, a pressure gradient will be required to force the droplets through pore constrictions. This "Jamin" effect can become appreciable as more droplets encounter pore throats. In addition to this effect, the adhesion of emulsion droplets on the surface of pores will increase the resistance to fluid flow and, thus, reduce the permeability. Other factors such as the migration of fine sand or clay particles with the emulsions will also contribute to the reduction of the permeability of cores. Migration of sand particles was tested by using fired and unfired cores (Berea sandstone) in the emulsion-generation experiments. With the fired core, the pressure gradient generated in the oil-alternating-surfactant solution injection was less than 36 psi within a 10-in-long core. However, with an unfired core, a greater increase in the pressure gradient with each cycle was created (in fig. 7).

McAuliffe's[1] concept of the mechanism by which an oil-in-water emulsions can cause a permeability reduction is shown in figure 8. Based on this mechanism, the droplets of oil in the emulsion should be slightly larger than the pore-throat constrictions in the porous medium. McAuliffe performed many experiments to verify his concept and to show that emulsion droplets can block high-permeability porous media. Soo et al.[6] conducted emulsion flow tests in a micromodel and observed the blockage effects described by McAuliffe. However, Uzoigwe and Marsden[7] tested the O/W emulsion flow in glass bead packs and did not show flow restriction. Unfortunately, none of these studies has determined the pore size distribution of porous media as compared with emulsion droplet size distribution. Some of the conclusions of these studies are questionable and may even be misleading. The following comments about the concept of emulsion blockage for permeability reduction are made.

1. The restriction of the flow of oil blobs or droplets through pore throats is the major mechanism for oil trapped in a formation after a waterflood. The injection of surfactant solution is supposed to reduce the interfacial tension (IFT) between oil and water phases and to help oil droplets or blobs to move. If droplet blockage is the major mechanism for sweep improvement, then increasing droplet size and interfacial tension, instead of using emulsifying agents to reduce IFT and droplet size, will be more favorable. So, the concepts involved are somewhat contradictory with respect to interfacial tension, as pointed out by Deck and Flock.[4] If oil droplet blockage is desired, oil can be dispersed in the water phase by mechanical blending, which will make larger oil droplets with higher IFT than emulsions.

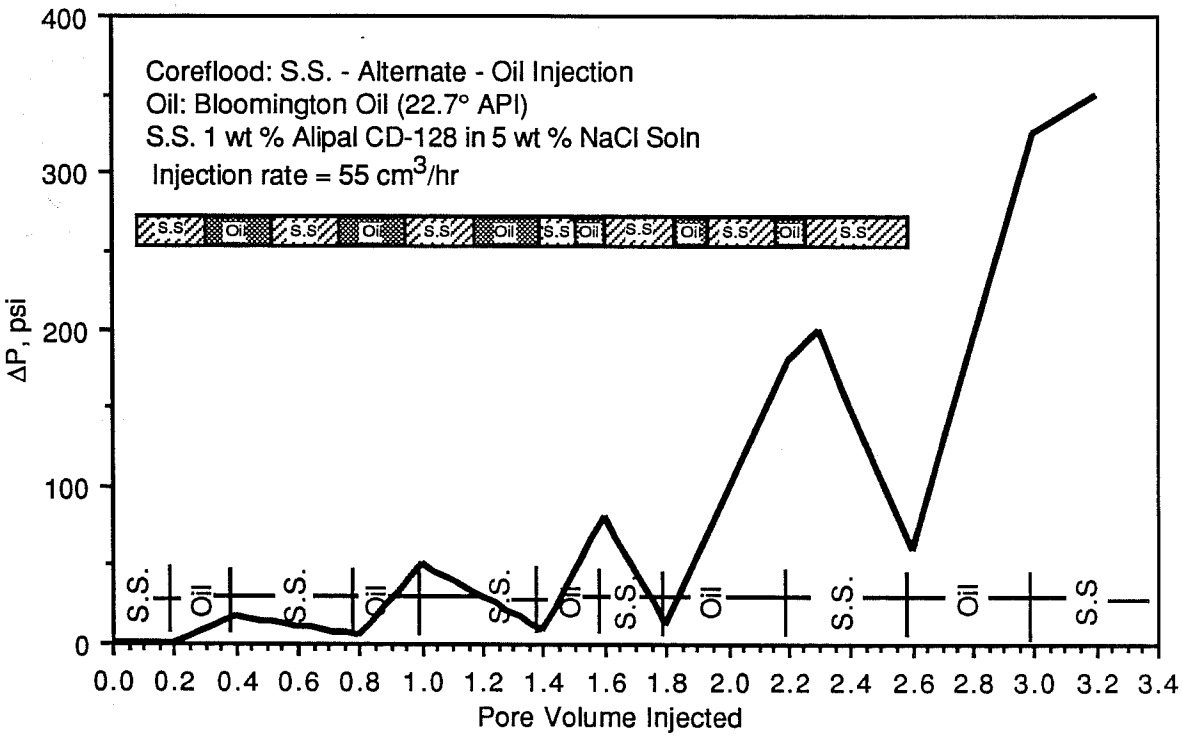


FIGURE 7. - ΔP across the core during the flooding of oil-alternating-surfactant solution injection.

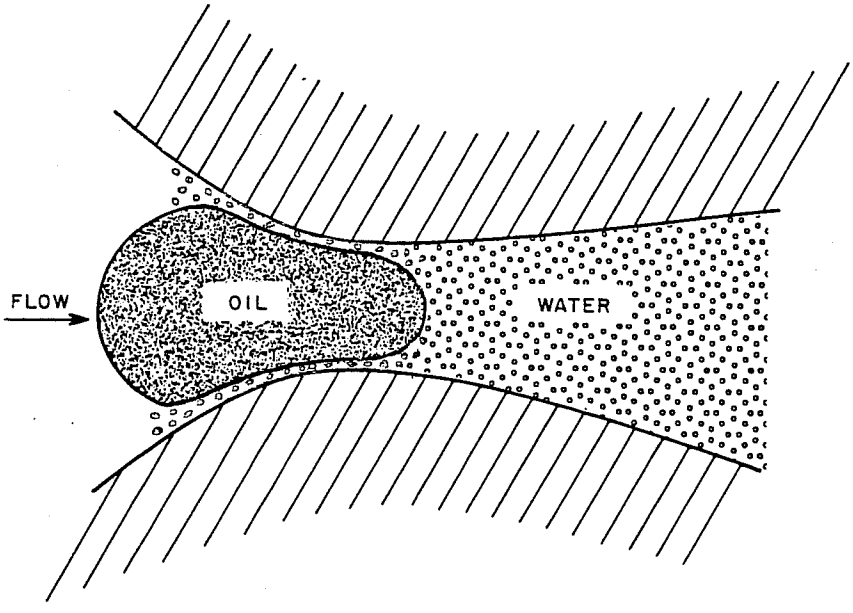


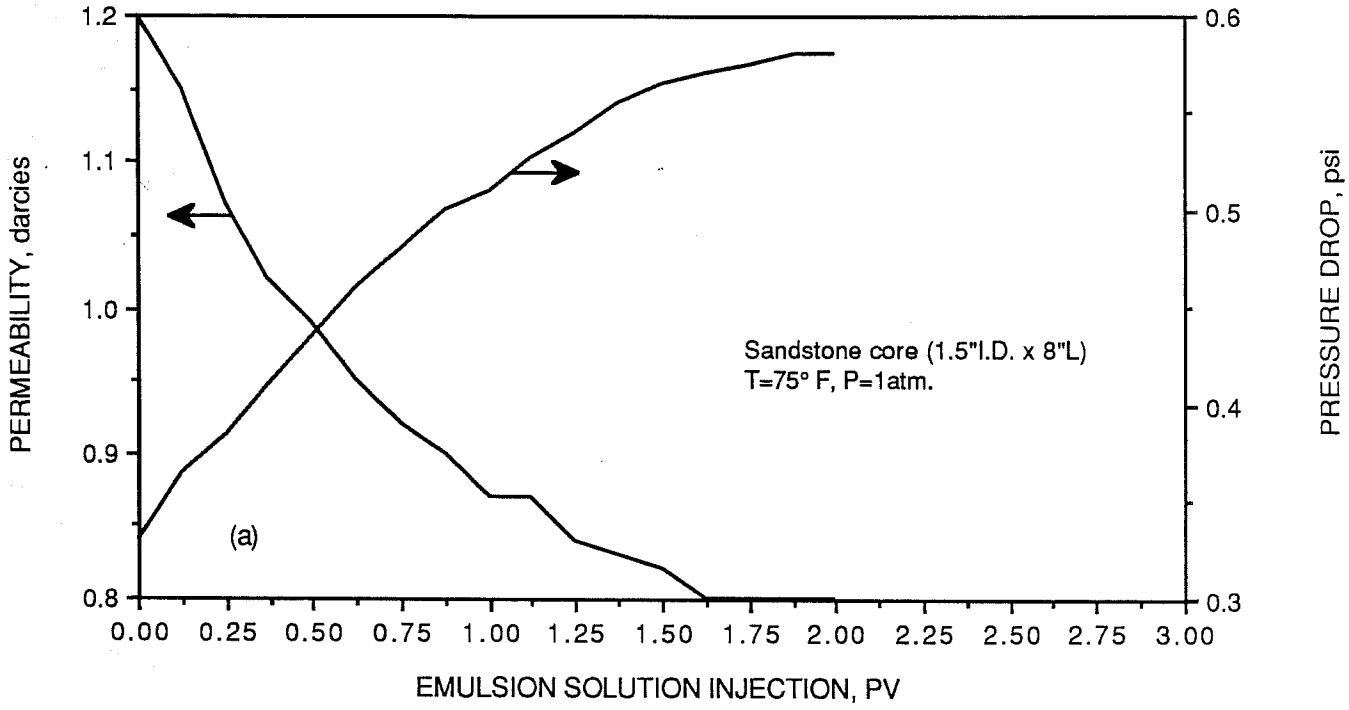
FIGURE 8. - Pore throat with oil droplet blocking water flow.

2. Since droplets that can block large pore throats will also block small pore throats, emulsions will not preferentially block high-permeability zones without blocking low-permeability zone. In parallel core experiments, McAluliffe[1] found that only the effluent from a high-permeability core contained emulsion whose oil concentration approached that of the injected emulsion, whereas effluents from low-permeability cores contained emulsions with smaller droplet sizes, which is a filtration phenomenon. McAuliffe's experiments also showed that after a great volume (12 PV) of emulsion had been injected, eventually both high- and low-permeability cores were reduced by the same order of magnitude in permeability. Part of the reason is due to the increase of oil saturation in high-permeability cores, which is a relative permeability phenomenon. At the same oil saturation, relative permeability depends on how the oil is distributed inside the core. So, the reduction of permeability with increasing oil droplet saturation is greater than that obtained by standard water-oil relative permeability measurements.

In this study, three fired cores with brine permeabilities of 1,200, 500, and 235 md were prepared for permeability-reduction tests. The medium-permeability (500 md) core was used for emulsion generation by injecting oil and surfactant solution alternatively into the core. The produced O/W emulsion was then injected into the high-permeability core and the low-permeability core to determine permeability reductions. Results of the pressure gradient increase and the permeability reduction for the high- and low-permeability cores are shown in figure 9. The viscosity effect has already been considered in permeability determinations. The percentage reduction in permeability is the same (33%) for both cores. Although the permeability reduction for the high-permeability core (from 1,200 to 800 md) is greater than that of the low-permeability core (from 235 to 155 md), resulting permeabilities for the low-permeability core are still lower than those of the high-permeability core. The permeability reduction for the high-permeability core is hardly explained by the theory of droplet blockage, since the emulsion was generated from a much lower permeability core. The estimated average pore diameter is about 19μ for the 1,200 md core. After the tests, brine was injected to displace the emulsion out of the cores. The effluent still contained a small amount of emulsion even after several pore volumes of brine had been injected. The oil droplets apparently are wedged in pore constrictions or retained on the pore surface by some electric interaction force.

EFFECT OF EMULSION ON GAS SWEEP EFFICIENCY

The application of externally produced emulsions for gas mobility control was tested. Two coreflooding experiments were conducted to test the effectiveness of injecting slugs of emulsions for the improvement of oil recovery in CO_2 flooding. A Berea sandstone core 1.5 ft long and 2-in. in diameter was



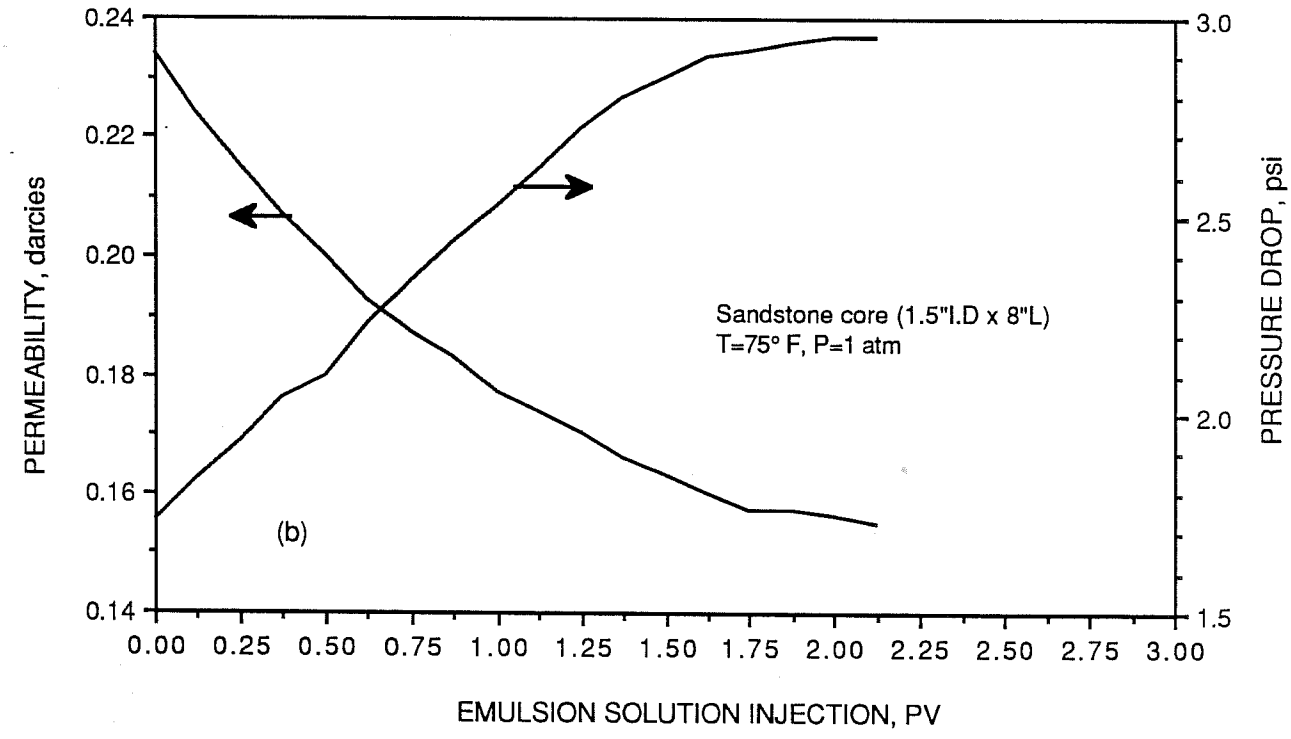


FIGURE 9. - Permeability reduction for (a) high-permeability (1,200 md) core, and (b) low-permeability (235 md) core.

used. The porosity of the core was 22.9%, and the brine permeability at testing conditions was about 260 md.

The first coreflooding test was a CO_2-alternating-brine (WAG ratio = 1:2) injection for the recovery of residual oil after waterflooding. The residual oil saturation after waterflooding was about 35.3% PV. The experiment was conducted at 142° F and 1,725 psig backpressure. The oil sample used was from Bloomington (TX) field. Carbon dioxide could not achieve miscibility with the sample oil under these conditions. The results are shown in figure 10. Oil recovery at 1.2 PV injection was about 40% of residual-oil-in-place (ROIP), and gas breakthrough occurred at 0.6 PV injection. Results from this experiment served as a baseline for comparison with the second coreflooding test of CO_2-alternating-emulsion (1:2 ratio) injection. The second coreflooding test was conducted at the same conditions and in the same core as the first one. The results are shown in figure 11. As compared with figure 10, gas breakthrough was significantly delayed. This shows that the injection of emulsion does improve gas mobility control. However, the recovery did not show substantial difference because the flooding test was conducted in a homogeneous, linear core which did not manifest a gas sweep problem. All these tests were conducted at low injection rates (5 cm^3/hr) to eliminate the formation of foam.

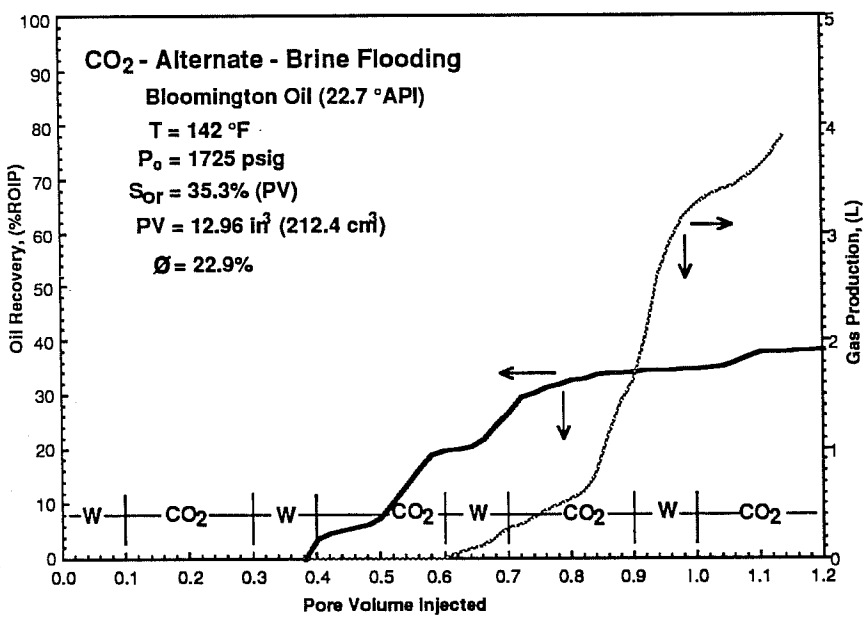


FIGURE 10. - Results of CO2-alternating-brine flood.

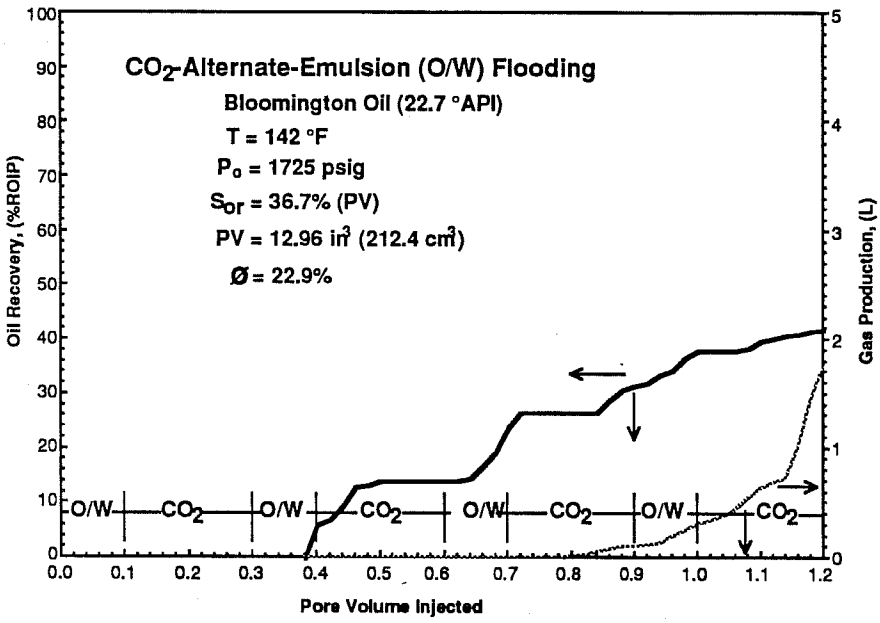


FIGURE 11. - Results of CO_2-alternating-emulsion flood.

CONCLUSIONS

1. The application of emulsion for gas sweep improvement or profile modification remains an unproven technique because the mechanisms of permeability reduction by emulsions are still not clear.

2. Injection of externally prepared emulsions into a porous medium can reduce its permeability, regardless of the original permeability.

3. Emulsions (O/W and W/O) can be generated in situ if the injected foamer solution can contact the oil in the formation.

4. Generated emulsions are stable even at high temperatures.

5. The viscosities of O/W emulsions are close to that of brine, whereas the viscosities of W/O emulsions is much higher than that of oil and exhibit non-Newtonian behavior at low shear rates.

6. Coreflooding tests showed no significant improvement in oil recovery by the CO_2-alternating-emulsion process but did delay gas breakthrough which might result in increased recovery in field applications.

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