

Microemulsions and Tertiary Oil Recovery

VINOD K. BANSAL AND DINESH O. SHAH

*Departments of Chemical Engineering
and Anesthesiology
University of Florida
Gainesville, Florida 32611*

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I. INTRODUCTION

Among various techniques suggested for tertiary oil recovery, the microemulsion flooding has received considerable attention in recent years. Microemulsion flooding can be applied over a wide range of reservoir conditions (1). The

In "Microemulsions: Theory and Practice,"
ed. by Leon M. Prince, Academic Press, 1977

use of microemulsions for oil recovery is not a recent development in petroleum technology. In 1959 Holm and Bernard (2) filed for a patent in which the use of surfactant dissolved in low-viscosity hydrocarbon solvent was proposed. In 1962 Gogarty and Olson (3) filed a patent describing the use of microemulsions in a new miscible-type recovery process known as Maraflood. In the late sixties more patents were issued to Jones, Cooke and Holm involving microemulsions for improved oil recovery (4). Recently Gogarty has reviewed the status and current appraisal of the microemulsion flooding process (5).

Generally speaking, wherever a water flood has been successful, microemulsion flooding will probably be applicable, and in many cases where water flooding has failed because of poor mobility relationships, microemulsion flooding can be successful because of the required mobility control. The recovery of oil from a reservoir is basically accomplished in three stages. In the primary oil recovery process, oil is recovered due to the pressure of natural gases which force the oil out through production wells. When this pressure is reduced to a point where it is no longer capable of pushing the oil out, water is injected to build up the necessary pressure to force the oil out. This is generally called the secondary oil recovery or water flooding process. The average oil recovery during the primary and secondary stages is about 30% of oil-in-place. To recover at least a part of the remaining 70% oil is the purpose of the tertiary oil recovery process. Various techniques used at this stage include carbon dioxide injection, steam flooding (thermal recovery) and surfactant flooding by either micellar or microemulsion solutions. The microemulsion flooding technique involves a decrease of capillary forces on oil droplets in the reservoir, thus improving oil recovery.

The microemulsion flooding process is a miscible-type displacement process. Two basic well configurations--the "five spot" pattern or the "line drive" pattern--are used for the microemulsion flooding process. In the "five spot" pattern (Fig. 1), four production wells are drilled at the corners of a square, and the injection well, through which the microemulsion is pumped, is at the center of this square. In the "line drive" pattern, production and injection wells are drilled in alternate rows.

In the microemulsion flooding process, the microemulsion slug is injected into the reservoir and is followed by a polymer solution for mobility control. This is in turn followed by the injection of water (Fig. 2). Microemulsions are optically transparent isotropic oil-water dispersions which can be formed spontaneously by using a combination of emulsifiers. The microemulsions used for oil recovery are composed

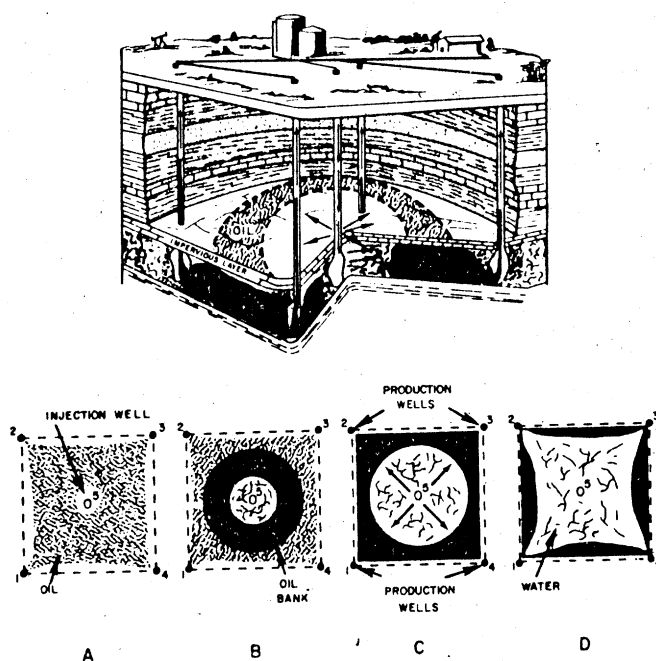


Fig. 1. The five-spot pattern of oil wells for displacement of oil in reservoirs.

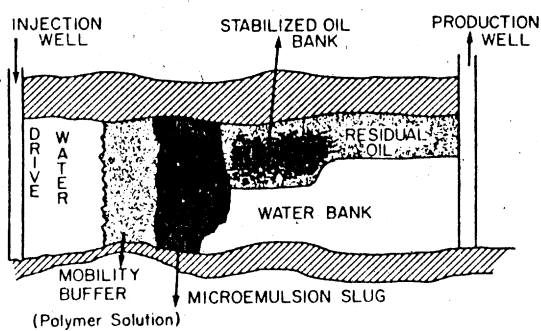


Fig. 2. A schematic presentation of microemulsion flooding process.

of hydrocarbons, surfactants, water and other organic liquids (alcohols) and are generally miscible with the reservoir oil and water. Microemulsions employed in this process may be either oil external (also called soluble oil) or water external. In most cases they contain crude oil from the reservoir in which they are to be injected.

The design of a microemulsion for a specific reservoir is basically a trial and error procedure. The formulation of the microemulsion slug for a particular reservoir depends upon the reservoir condition after the secondary recovery process and the properties of the microemulsion slug itself.

Petroleum sulfonates are the most widely used surfactants in the preparation of a microemulsion slug. The chemistry of these petroleum sulfonates and the interfacial properties of the system have to be fully understood for any successful microemulsion flooding process. Unfortunately our understanding of the theoretical aspect of the microemulsion flooding process is far from clear.

In section 2 of this chapter, the role of the capillary and hydrostatic forces on the entrapment of oil in the reservoir, and the necessary conditions for the displacement of this entrapped oil will be discussed. Following this, sections 3 and 4 will deal with important properties of a microemulsion slug required for the tertiary oil recovery. Finally, the economic aspect of the process (profitable microemulsion slug) will be discussed.

II. ROLE OF CAPILLARY AND VISCOUS FORCES ON OIL RECOVERY

Under ordinary flooding conditions (water or immiscible fluid), surface forces (capillary forces) dominate the macroscopic displacement process and are responsible for trapping a large portion of the oil within the pore structure of the reservoir rocks. The microscopic distribution of the trapped oil depends upon the hydrostatic equilibrium condition and is a function of factors such as wettability of the rock and pressure in the fluid phases. If the flood rate is made sufficiently high, however, the viscous forces dominate the macroscopic displacement process (6). In order to determine whether viscous or capillary forces are dominating the displacement process, it is convenient to consider the dependence of the displacement efficiency on a suitable dimensionless parameter. Such a number is the capillary number (N_{ca}) which is defined as

$$N_{ca} = \frac{\mu_w U_w}{\phi \gamma_{ow}} \quad (1)$$

where μ_w and U_w are the aqueous phase viscosity and flow rate per unit cross sectional area, γ_{ow} is the interfacial tension between oil and water and ϕ is the porosity of the reservoir rock structure (7). Physically, the capillary number represents the ratio of viscous to capillary forces. The capillary number for an ordinary waterflooding process is of the order of 10^{-6} (7).

Laboratory studies, using either sandpacks or Berea cores, to determine the relationship between the capillary number and the percent residual oil saturation have been carried out by various workers (6,7). The studies involved increasing the flood rate, and/or decreasing the interfacial tension. Sometimes an increased aqueous phase viscosity, μ_w , was also used. All these studies were preceded by a conventional water flooding. As the capillary number was increased by adjusting μ_w , U_w , and γ_{ow} the displacement efficiency also increased. It appears that in order to reduce the value of the residual oil saturation by a factor of about one half, it is necessary to increase the capillary number (N_{Ca}) by a factor of 1000. Work reported by Foster (Fig. 3) indicates that increasing N_{Ca} by a factor of 10,000 will result in a microscopic displacement efficiency approaching 100% (7). The displacement efficiency is basically the percentage of the oil recovered by this method. The upper critical value of the capillary number for 100% efficiency was found to be of the order of 10^{-2} to 10^{-1} . The correlation between displacement efficiency (percent residual oil) and capillary number, as obtained from laboratory experiments under tertiary recovery conditions, strongly suggests that the process of mobilizing residual oil depends on a competition between viscous and capillary forces.

Figure 4 illustrates the interplay of capillary and viscous forces in the water flooding process. Shown in the figure is water displacing oil in two capillaries of radii r_1 and r_2 , respectively.

The relationship between the velocity ratio of these two interfaces in the pore structure, and the viscous and capillary forces is given below (8):

$$\bar{V} = \frac{V_1}{V_2} = \frac{\frac{4Lq_w}{\pi r_2^2 \sigma \cos \theta} + r_2^2 \left(\frac{1}{r_1} - \frac{1}{r_2} \right)}{\frac{4Lq_w}{\pi r_1^2 \sigma \cos \theta} - r_1^2 \left(\frac{1}{r_1} - \frac{1}{r_2} \right)} \quad (2)$$

where V_1 and V_2 are the velocities of the interface in capillaries 1 and 2 of radii r_1 and r_2 , respectively; q is the fluid (aqueous phase) flow rate; μ is the viscosity of the fluid, L is the distance over which the capillary and viscous forces are competing (length of pore); σ is the interfacial tension between oil and water; and θ is the contact angle measured in the displacing phase.

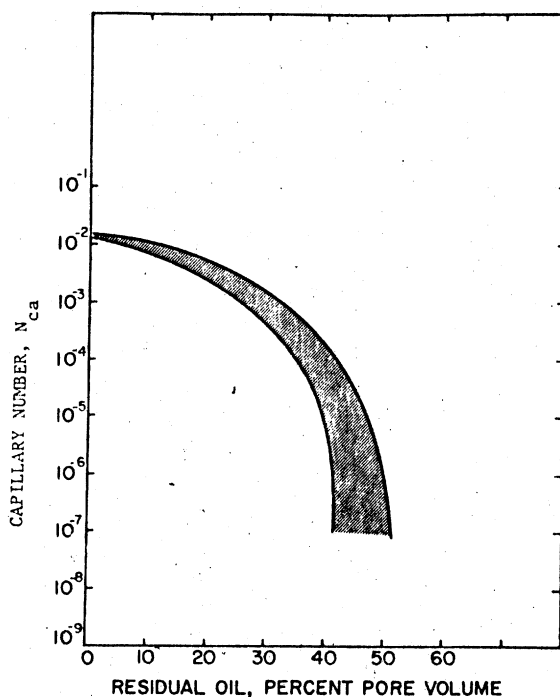


Fig. 3. The dependence of residual oil saturation of capillary number. Reproduced from Foster (7), courtesy of Society of Petroleum Engineers of A.I.M.E.

When capillary forces are negligible in comparison to the viscous forces, the last term in both the numerator and denominator in the above equation may be neglected. In such a case, the equation reduces to:

$$V = \frac{r_1^2}{r_2^2} \quad (3)$$

Under these conditions the rate of flow is proportional to the square of the radius and consequently the residual oil is left in the smaller openings.

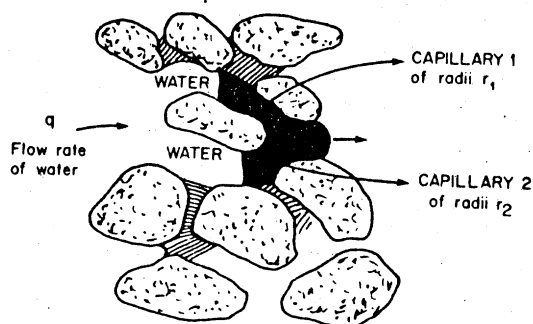


Fig. 4. A model of capillaries in a porous medium. Reproduced by Moor and Slobod (8), courtesy of Producers Publishing Co., Inc.

When the capillary forces are large compared to the viscous forces, the first term in both numerator and denominator in the equation (2) may be neglected. In such a case, equation (2) reduces to

$$\bar{V} = - \frac{r_2^2}{r_1^2} \quad (4)$$

This suggests that the flow will be faster in the smaller capillaries and the residual oil will be left in the larger capillaries.

Taber et al. (9) correlated the oil displacement with the ratio $\Delta P/L\sigma$, where ΔP is the pressure drop across the distance L and σ is the interfacial tension between the oil and water. The critical ratio of $\Delta P/L\sigma$ is defined as that value below which no residual oil is produced from any of the porous media. After the critical pressure gradient was exceeded for each sample, it was possible to produce larger quantities of the residual oil by merely increasing the value of $\Delta P/L\sigma$.

Taber et al. (9) have shown a correlation between the $(\Delta P/L\sigma)$ critical and the viscosity of aqueous phase and oil and the permeability of porous media. The value of the critical $\Delta P/L\sigma$ ratio increases with either an increase in viscosity of the oil or aqueous phase or with a decrease in the permeability of the porous media. Their results for the residual

oil displacement from rock samples of different permeabilities appear to have much more relevance to oil recovery than the modest viscosity effects noted with either the aqueous or oil fluids. The critical values of $\Delta P/L\sigma$ ranged from a high value of 23.28 for a core with an air permeability of 95 md to a low value of 0.31 for the most permeable sample (2190 md). The correlation between permeability and the critical displacement ratio $\Delta P/L\sigma$ is shown in Fig. 5. The lower permeability values

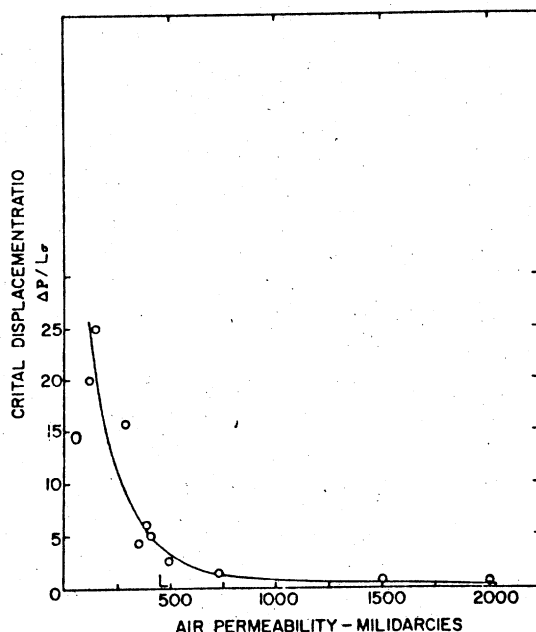


Fig. 5. The relationship between permeability and the critical value of $\Delta P/L\sigma$. Taber, Kirby and Schroeder (9), courtesy of the American Institute of Chemical Engineers.

mean that significantly higher values of $\Delta P/L\sigma$ must be achieved before any residual oil can be displaced from a porous rock.

Stegemeier (10) has presented an "alternate path" theory for residual oil saturation and petrophysical properties over a broad range of varying interfacial and viscous conditions. His model allows for intermediate water wetting up to 90° (contact angle) and discontinuous trapped oil in single or in interconnected pores. A quantitative expression relating the capillary pressure to various properties of fluid and rock was derived by Stegemeier. It was concluded that for a given combination of fluid properties and applied pressure differential, all of the non-wetting phase will be removed from pores

having capillary pressures less than that calculated from his equation.

Slattery and Oh (11) carried out theoretical analysis for the critical pressure gradient on an ideal system of pores where the pore radius is a sinusoidal function of axial position. He concluded that for the most efficient displacement of residual oil, the porous structure should be water-wet and that intermediate wettability may be less desirable than either oil wet or water wet behavior. His estimate of the critical value of the pressure gradient agrees with the experimental data of Taber *et al.* (9) to within 50%.

III. DESIRABLE PHYSICO-CHEMICAL PROPERTIES OF MICROEMULSION SLUG

The design of a microemulsion slug for the tertiary oil recovery process is basically a trial and error procedure. However, there are some basic properties of a microemulsion slug and the effect of some particular variables on these properties that have to be studied before any laboratory and field test of a particular microemulsion slug is warranted. The success of the microemulsion flooding process for tertiary oil recovery depends on a proper choice of the chemicals that go into the formation of the microemulsion slug. The composition of the microemulsion slug is dependent upon the properties required of the microemulsion slug as well as on the conditions prevalent in the reservoir. In this section some important properties of microemulsions, as applicable to tertiary oil recovery, will be discussed.

A. Phase-equilibrium and Solubilization

Microemulsions used for improved oil recovery contain at least three components: oil, surfactant, and brine. Hence, the compositional state of the system must be specified by at least three numbers. It is, therefore, both convenient and instructive to employ a ternary representation for a phase equilibrium study.

Several studies (12-18) on ternary diagrams of microemulsion systems having application to oil recovery have been done. Using measurements of viscosity, electrical resistivity, optical birefringence and a phase disappearance technique, these studies have investigated structural changes in the microemulsion as a function of composition. A simple ternary diagram for such a three component system is shown in Fig. 6, where S, W, O and M represent surfactant, water, oil and microemulsion, respectively.

The effectiveness of the microemulsion flooding process

depends upon the extent of the single phase region in the ternary diagram of interest. The microemulsion flooding process can be prolonged by minimizing the vertical extent of the multiphase region in the ternary diagram. Reed et al. (15) introduced the concept of optimal salinity for a microemulsion

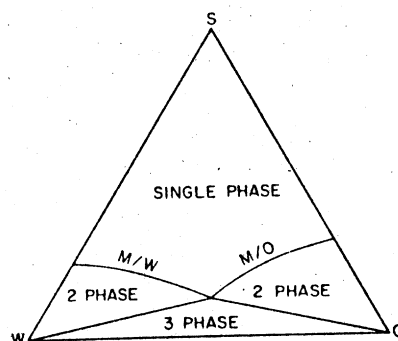


Fig. 6. Idealized ternary diagram for surfactant-oil-water systems. Reproduced from Robbins (12), courtesy of the Society of the Petroleum Engineers of A.I.M.E.

single phase to determine the minimum area of the multiphase region. As defined by them, the optimal salinity can be determined by plotting the surfactant concentration required to make a 50:50 water:oil mixture a single phase as a function of salt concentration as shown in Fig. 7. For this case, the graph exhibited a minimum near 1.25% NaCl and this salt concentration was defined as the "optimal salinity" for the given system. From the ternary diagram of the same system it was found that the minimum area of the multiphase region also occurred at 1.25% NaCl. Thus the determination of the optimal salinity for a given system assists in the determination of the formulation of a microemulsion for the tertiary oil recovery process. The effect of divalent ions (Ca^{++}) on the optimal salinity was also investigated by Reed et al. (15) (Fig. 8). They observed that Ca^{++} reduced the optimum salinity from 1.25% NaCl to 1.1% total solid (1.0% NaCl + 0.1% CaCl_2). These microemulsions have a salt tolerance limit beyond which they are not stable. To increase the salt tolerance of these microemulsions various alcohols (cosolvent) are added. The salt tolerance of a microemulsion is an important consideration, since the natural salt concentration in the reservoir can be very high.

The effect of various alcohols on the solubilization of brine has been studied by Jones and Dreher (19). It was observed that water soluble alcohols solubilize additional brine

into a microemulsion. Water insoluble alcohols, however, cause solubilization of hydrocarbon, while decreasing the brine solubility. It was also observed that for a stable microemulsion, an increase in electrolyte concentration decreases the water-insoluble alcohol requirements and reduces the breadth of the single phase region. Conversely, an increase in electrolyte concentration increases the water-soluble alcohol requirements.

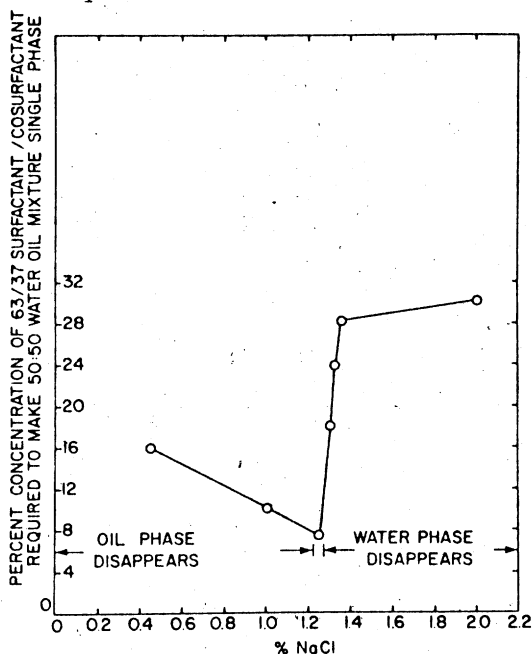


Fig. 7. The optimum salinity for mixtures of oil and water. Reproduced from Healy and Reed (15), courtesy of the Society of Petroleum Engineers of A.I.M.E.

B. Phase Volume Ratio and Bulk Rheological Properties

As was discussed in the previous section the important region of the ternary diagram for the tertiary oil recovery process is the single phase region. In this single phase region, the microemulsion goes through a number of structural changes between the water external and oil external extremes. In a recent study Shah et al. (20) have shown, using electrical, birefringence and high resolution NMR measurements, that upon increasing the amount of water in an oil external microemulsion, the structure of the microemulsion passes through transitions from water spheres (oil external) to water cylinders to water lamellae and finally to a continuous water

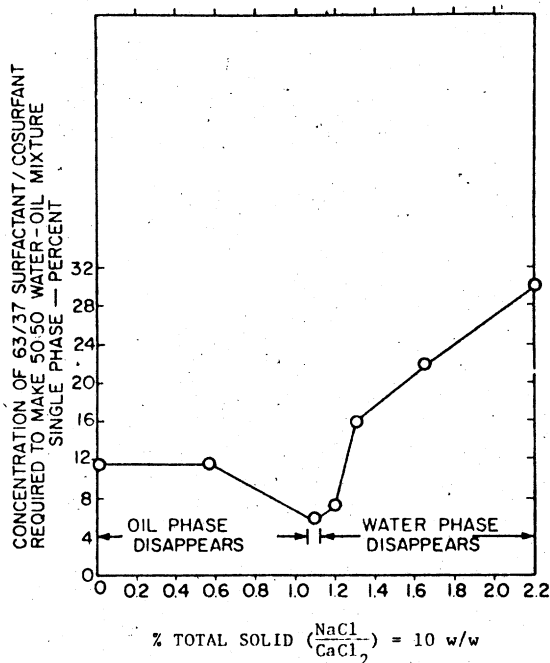


Fig. 8. Effects of Ca^{++} on optimum salinity for mixtures of oil and water. Reproduced from Healy and Reed (15), courtesy of the Society of Petroleum Engineers of A.I.M.E.

external phase. (The figure was shown previously in Chapter 1.) The addition of water to an oil external microemulsion causes an increase in the size and number of dispersed water droplets. Since the total amount of surface active agent in the system remains constant, further addition of water would increase the interfacial area of the water spheres, decrease the surface concentration of the surfactant, and hence increase the interfacial tension. At some concentration of water the intermolecular forces at the oil-water interface would be insufficient to hold the interface together, and the spherical droplets of water would collapse to form cylinders of water. Using the same reasoning, further dilution with water will cause a transition from the cylindrical structure to a lamellar structure. Upon still further addition of water the lamellar structure changes to spherical oil droplets which are dispersed in a water phase.

The effect of interfacial forces and the structural changes discussed above on the bulk viscosity of microemulsions is shown in Fig. 9 (21). The system used for relative viscosity measurements consisted of Hexadecane (oil) + Hexanol (cosolvent) + K-oleate (surfactant). The microemulsion used

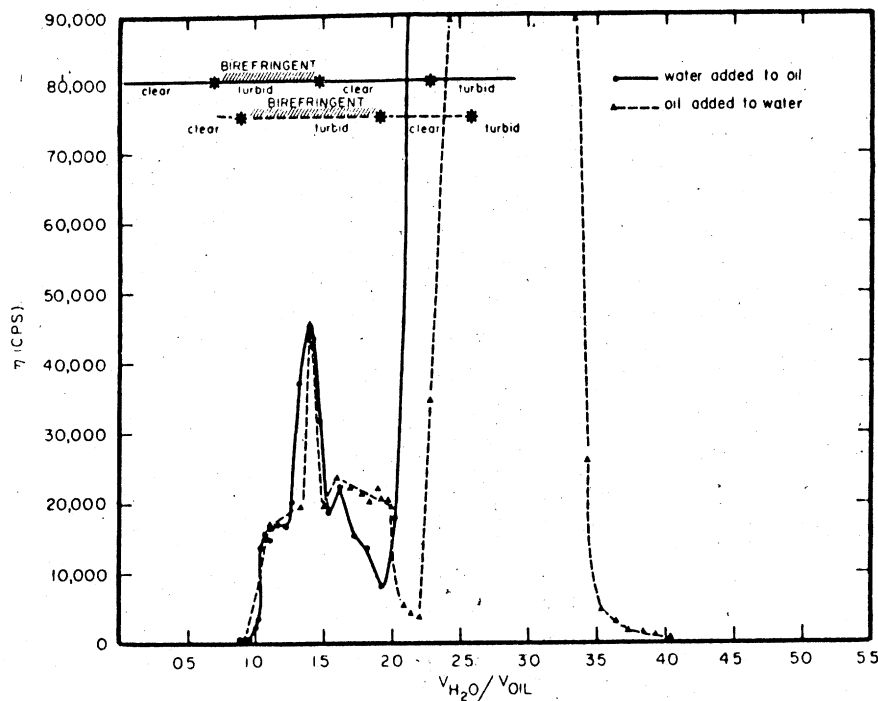


Fig. 9. The effect of water-oil ratio on viscosity of microemulsions and phase-inversion region of Hexadecane-water-oleate-hexanol system. Reproduced from Shah, Falco and Walker (21), courtesy of American Institute of Chemical Engineers.

had a constant ratio of 10 ml hexadecane: 4 ml hexanol: 2 gm of K-oleate. The relative viscosity data for different water/oil ratios is shown in Fig. 9. From this figure it is seen that there is a maximum in the relative viscosity at a water/oil ratio of 1.4. This maximum in the relative viscosity corresponds to a lamellar structure occurring at this ratio. The viscosity peak observed between the water/oil ratios of 2.0 and 3.5 was beyond the experimentally measurable limit. It was found that both these viscosity peaks were observed upon either increasing or decreasing the water to oil (Hexadecane) ratio. It was also observed that the dispersion having a lamellar structure at the water:oil ratio of 1.4 was very viscous upon its formation, with the viscosity subsequently decreasing with time.

The effect of shearing time, at a constant shear rate, on the viscosity of these lamellar structures is shown in Fig. 10. The viscosity initially increases with shearing time and then levels off to a steady value. The effect of age of the solution on the viscosity shows that as the age increases the viscosity of these lamellar structures decreases. The initial increase in the viscosity with shearing time can be attributed to disordering and entanglement of the lamellar structure upon shearing (Fig. 11).

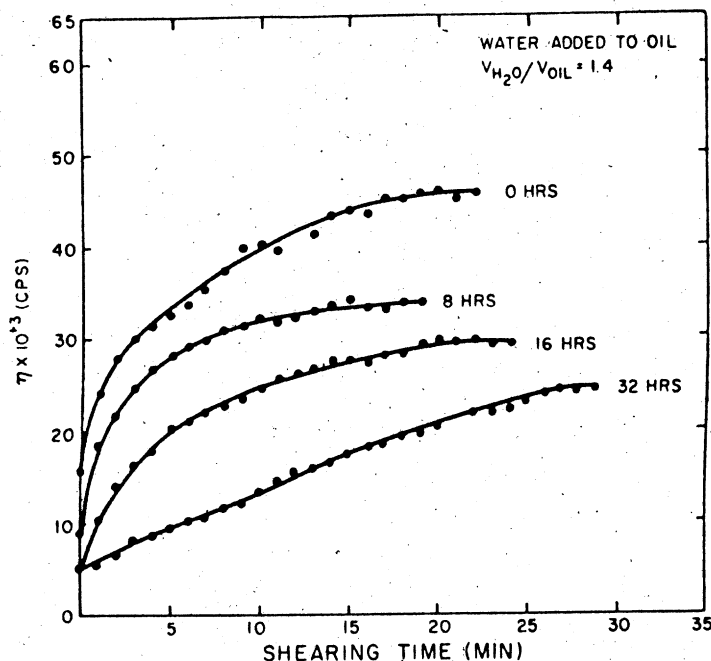


Fig. 10. The effect of shearing time on viscosity of microemulsions. Reproduced from Shah, Falco and Walker (21), courtesy of American Institute of Chemical Engineers.

In tertiary oil recovery by microemulsion flooding, the stability of the microemulsion slug is an important consideration. In particular its mobility (as defined in a later section) has to be controlled. The mobility is inversely proportional to its viscosity and hence a very large viscosity is undesirable. This would cause plugging of the pores with consequent loss of surfactant. Hence it is advisable to stay out of the range of gel formation (lamellar structure) or to avoid

it by adjusting the composition of the microemulsion. Alternatively, a shift in the viscosity peak could be achieved through a manipulation of the salt, oil, surfactant or co-solvent concentrations.

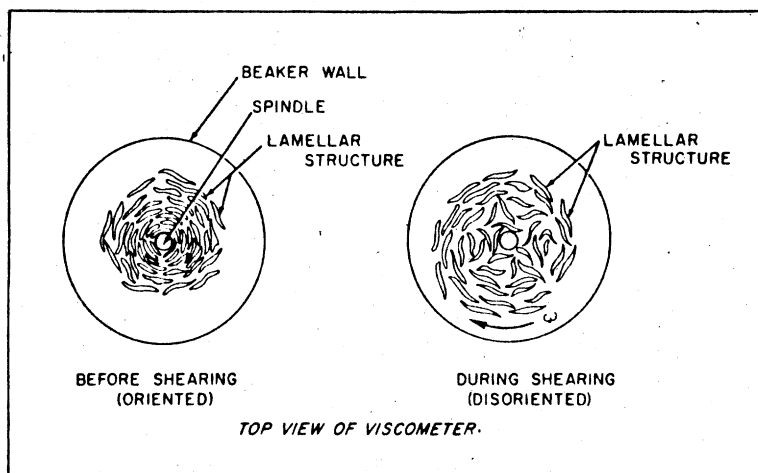


Fig. 11. The effect of shear time on the orientation of lamellae in a lamellar liquid-crystalline phase. Reproduced from Shah, Falco and Walker (21), courtesy of American Institute of Chemical Engineers.

C. Interfacial Tension

The interfacial tension between the crude oil and the displacing liquid (microemulsion) is one of the major parameters which has to be controlled and fully determined before the microemulsion slug can be used for any tertiary oil recovery process. Healy and Reed (22) used the Laplace equation

$$\Delta P = 2\gamma \left(\frac{1}{r_1} - \frac{1}{r_2} \right) \quad (5)$$

to calculate the pressure difference (ΔP) across an oil drop having a curved interface with principal radii r_1 and r_2 , and an interfacial tension γ between the oil and water. Using an electroscan micrograph of a cross section of the porous medium they calculated the pressure the water would have to develop in order to displace the largest entrapped oil droplet observable in the micrograph. This would correspond to the lowest pressure drop (largest drop size) necessary to begin displacing the oil. Using a normal oil/water interfacial tension of

the order of 10 dynes/cm, the calculated pressure drop turned out to be $\approx 5 \times 10^2$ psi/ft, while a practical limit to pressure drops achievable under field conditions is about 1-2 psi/ft. Under this practical limitation, the most obvious solution to displacement of the entrapped oil is through a reduction in the crude oil/displacing liquid interfacial tension to about 0.001 dyne/cm.

The microemulsion slug used in the tertiary oil recovery process should effectively displace oil at the front, and should be effectively displaced by drive water at the back, as illustrated in Fig. 2. For an efficient process, both these are essential requirements, and therefore the interfacial tensions at the microemulsion-oil interface (γ_{mo}) and the microemulsion-buffer solution interface (γ_{mw}) should be very low as has already been discussed. The conditions where these two interfacial tensions are both low and equal to each other is of particular significance in designing a microemulsion slug for the process. The equality condition arises from the definition of the capillary number and helps to ensure stable movement of various banks. A large difference in N_{Ca} at the two interfaces would lead to different pressure gradient requirements for each interface.

Healy and Reed (22) have studied the effect of NaCl concentration on the interfacial tension γ_{mo} and γ_{mw} and the effect on the solubilization parameters V_o/V_s and V_w/V_s (where V_s = volume of surfactant in the microemulsion not including cosolvent, and V_o and V_w are the volumes of oil and water in the microemulsion phase, respectively). The results obtained by them are shown in Fig. 12. It was found that an increase in salinity decreases γ_{mo} and increases γ_{mw} . The point of intersection of γ_{mo} and γ_{mw} was defined as the "interfacial tension optimal salinity" (C_y). Determination of the interfacial tension optimal salinity assists us in designing a microemulsion slug because of the above stated conditions for γ_{mo} and γ_{mw} . The phase behavior optimal salinity, C_ϕ , is defined by the intersection of V_o/V_s with V_w/V_s . The correlation between C_y and C_ϕ is apparent, and this indicates that phase volumes can replace interfacial tension measurements as a preliminary measure of interfacial activity, thus markedly reducing the labor involved.

The effect of hexanol (cosolvent) and K-oleate (surfactant) on the interfacial tension was determined by measuring the average drop volume of water in hexadecane by Shah (20). This method consists of squeezing the smallest possible water drop out of a microsyringe into a bath of hexadecane. The smaller the drop volume of water, the lower is the interfacial tension. The results of these measurements are given in Table I. This table illustrates the effect of the various constituents in a microemulsion (Hexadecane + Hexanol + K-oleate + water) on the average drop volume of water (with or without

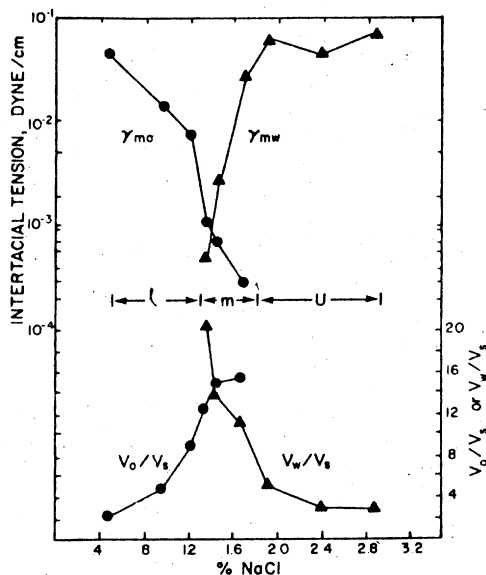


Fig. 12. The effect of salt concentration on the interfacial tension and solubilization parameter in oil-brine-surfactant-alcohol system. Reproduced from Healy and Reed (22), courtesy of American Institute of Chemical Engineers.

additives) in hexadecane (with or without additives). The results show that Potassium oleate, even at low concentrations, is more effective than hexanol in decreasing the average drop-volume of the water drops. However, the presence of hexanol and potassium oleate in hexadecane and water, respectively, decreases the drop volume to less than 10^{-6} ml. This decrease in drop volume by the addition of both hexanol and K-oleate indicates the drastic decrease in interfacial tension between Hexadecane and water made possible by this addition.

In practice various petroleum sulfonates have been employed in the formulation of microemulsions which exhibit ultra-low interfacial tension with oil as well as with the aqueous phases. It has been shown (23) that a petroleum sulfonate with an equivalent weight distribution that is relatively narrow and/or symmetrical about the median is the most effective in lowering interfacial tensions. A minimum in interfacial tension can also be achieved through an adjustment of the electrolyte content of the aqueous phase (23). Sodium chloride was found to be more effective than sodium sulfate, carbonate or tripolyphosphate in decreasing the interfacial

tensions between the oil and the aqueous phase (23).

TABLE I

Effect of Hexanol and Potassium Oleate on the Average Volume of Water Drops in Hexadecane

Interfacial Composition		Average Drop-Volume
Hexadecane (oil)	Water	
No additive	No additive	2.8×10^{-2} ml
Hexanol		
0.1 ml/ml of oil	"	6.0×10^{-3} ml
0.4 ml/ml of oil	"	5.0×10^{-3} ml
0.6 ml/ml of oil	"	5.0×10^{-3} ml
No additive	K-oleate	
"	0.02 gm/ml of water	8.0×10^{-4} ml
"	0.56 gm/ml of water	8.0×10^{-4} ml
"	0.1 gm/ml of water	4.4×10^{-4} ml
Hexanol	K-oleate	
0.025 ml/ml of oil	0.06 gm/ml of water	1×10^{-4} ml
0.05 ml/ml of oil	"	6.6×10^{-5} ml
0.075 ml/ml of oil	"	volume $< 10^{-6}$ ml

IV. MOBILITY CONTROL DESIGN FOR THE MICROEMULSION PROCESS

Adequate mobility control is an important requirement for any microemulsion flooding process. Mobility control of the process implies changing the properties of the injected fluids such that a stable movement of the separate banks is achieved with a minimum of mixing and dispersion. The mobility of a fluid is defined by $\lambda = k/\mu$, where λ is the relative mobility of the fluid with a relative permeability of k and a viscosity μ . Without a mobility control slug following the microemulsion slug, the integrity of the microemulsion slug is jeopardized after its injection into the reservoir, and large pore volumes of the microemulsion slug are required for the process to proceed. Mobility control for the process is based upon the total mobility of the oil and water flowing ahead of the slug in a stabilized bank. For an ideal system, the mobility of the microemulsion slug is made equal to or less than that

of the oil bank. The mobility of the buffer is made equal to or less than that of the microemulsion slug.

The mobility of a stabilized oil bank is calculated (24) using the following equation

$$q_{tb} = KA \left(\frac{\Delta P}{\Delta L} \right)_b (\lambda_{rw} + \lambda_{ro})_b \quad (6)$$

where q_{tb} = Total flow rate in the stabilized oil/water bank

K = Absolute permeability

A = Cross sectional area

$\left(\frac{\Delta P}{\Delta L} \right)_b$ = Average pressure gradient in the stabilized oil/water bank

$(\lambda_{rw} + \lambda_{ro})_b = \left[\frac{K_{rw}}{\mu_w} + \frac{K_{ro}}{\mu_o} \right]_b$ = Total relative mobility in the stabilized oil bank

where K_{rw} = Relative permeability with respect to water

K_{ro} = Relative permeability with respect to oil

and μ_w and μ_o are the viscosity of water and oil, respectively.

The total relative mobility can be obtained as a function of water saturation from relative permeability data for the aqueous phase and the oil phases (24). The use of such data enables the appropriate fluid viscosity and total relative mobility to be plotted as a function of water saturation. A typical curve for a reservoir plotting the total relative mobility as a function of water saturation is shown in Fig. 13. The stabilized oil bank should not have a mobility less than the minimum seen in the figure, and thus this minimum mobility value represents a design mobility value.

A. Microemulsion Slug Mobility

The first step in a mobility design procedure is the control of the mobility of the microemulsion slug. The mobility of a microemulsion is a function of its composition and can be controlled to fit a specific application. The parameters that can be varied to control the mobility of the microemulsion slug are the amount of water, the electrolyte concentration, the type of hydrocarbon and surfactant used and the use of co-surfactants. Care should be taken not to make a change in mobility control that adversely affects the other properties of the microemulsion and consequently its ability to displace the oil.

Figure 14 (25) illustrates the effect of water content on the viscosity of a microemulsion. The microemulsion contained a constant ratio of 76% Pentane to 19% sulfonate to 5% Isopropanol. Pentane, sulfonate and Isopropanol together represent

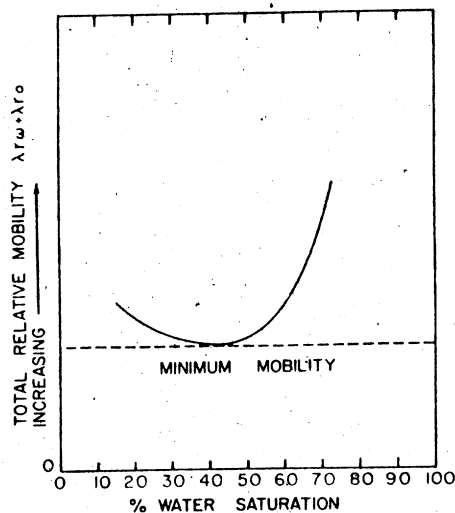


Fig. 13. The effect of percent water saturation on the total relative mobility of oil and water. Reproduced from Gogarty, Meabon and Milton (24), courtesy of the Society of Petroleum Institute of A.I.M.E.

one component and the water content (the second component) was varied to obtain different compositions. Upon addition of water to an oil external microemulsion there is an exponential increase in the microemulsion viscosity up to a water concentration of about 45%. This is the inversion point for this system and represents the point where the oil-external character of the system switches over to a water external one. Figure 14 also illustrates the use of electrolyte in controlling the viscosity. It was found that the viscosity could be reduced by up to two orders of magnitude with the addition of less than 0.3% Na_2SO_4 to the above microemulsion. It was also observed that the addition of cosurfactant caused a reduction in viscosity. Usually an order of magnitude reduction in viscosity is not uncommon with the addition of 1 to 2 percent of either isopropanol or normal butyl alcohol.

B. Mobility of Buffer (Polymer) Slug

For an efficient microemulsion flooding process the mobility of the buffer displacing the microemulsion slug is one of the important factors to be taken into account in designing the process. As mentioned, for a stable system, the mobility of the buffer solution must be equal to or less than the mobility of the microemulsion slug (24). Higher mobility of

buffer solution causes the "fingering" of polymer solution into the microemulsion slug. Water thickened by the addition of a polymer serves as an effective mobility buffer solution. Many polymers have been reported to be effective mobility control agents (26). However, polyacrylamides are the only polymers that have been used as mobility control agents on a large scale. Mobility control with polyacrylamides is achieved through a reduction in both the viscosity and the permeability (27). Both the molecular weight and the degree of hydrolysis of the polymer are important characteristics in the design of a mobility control solution (27).

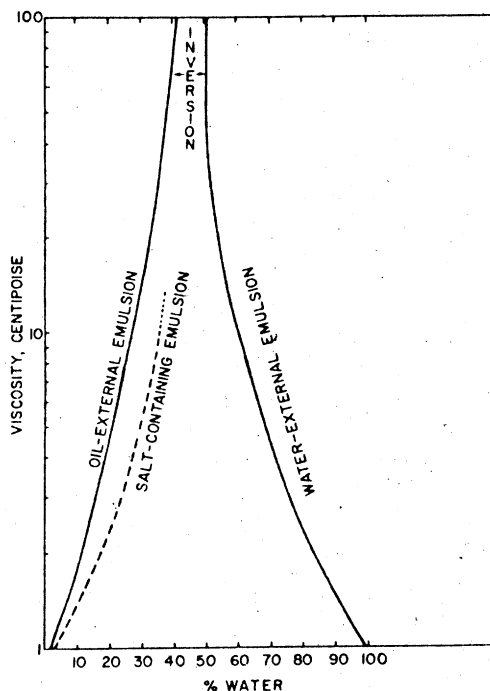


Fig. 14. The effect of percent water on the viscosity of microemulsions. Reproduced from Gogarty and Tosch (25), courtesy of the Society of Petroleum Institute of A.I.M.E.

V. ECONOMIC ASPECTS OF THE PROCESS

A. Economic Aspects of Mobility Control

The cost of the mobility buffer solution and microemulsion slug depends upon their respective compositions. The

microemulsion slug mobility can be reduced to almost any value by changing the composition of the microemulsion, and normally the cost variation entailed in changing the composition of the microemulsion is insignificant. The mobility of the microemulsion slug can thus be adjusted to a value much lower than the design mobility without significantly affecting its cost. However, a low value for the mobility of the microemulsion slug requires a higher concentration of polymer (in the buffer solution) in order to ensure adequate mobility control at the buffer-microemulsion slug interface. From an economic standpoint, the cost of the mobility buffer solution is related to its polymer concentration, and hence, the polymer concentration should be kept to a minimum (1). The cost of the polymer used in the mobility buffer imposes a restraint upon the lowering of the slug mobility. For this reason the mobility of the buffer solution is made only slightly less than the design mobility. Cost of buffer permitting, buffer injection continues until the flood is completed. This is because the injection of drive water behind the mobility buffer can cause an unfavorable condition, since the drive water can penetrate and bypass the mobility buffer and slug and change the process from tertiary to ordinary water flooding.

B. Economic Aspects of the Microemulsion Slug

The cost of the chemicals used in the formulation of microemulsions for the flooding process and the oil saturation in the reservoir at the time the process is initiated determine whether the process is economically feasible or not. Of all the chemical components making up a microemulsion slug, the surfactant, petroleum sulfonate, is the most expensive component. The cost of the microemulsion can be decreased considerably by developing a new formulation that uses a lower surfactant concentration, lower cosurfactant concentration and also by using the crude oil in place of refined hydrocarbons. Economic success or failure of the microemulsion flooding process depends largely upon the proper choice of a microemulsion slug size. Jones (28) describes a simple technique for estimating "optimum slug size." Optimum slug size is defined as that slug size that will maximize the profit. The data required to determine the "optimum slug size" includes oil price, average oil saturation, per-barrel slug cost, and a slug size vs. oil recovery curve. The slug size versus oil recovery curve can be obtained either from laboratory tests or pilot field tests, preferably from the latter. According to his derivation maximum profit would occur when the following condition is satisfied:

$$\frac{\delta R_o}{\delta V_s} = \frac{C_s}{S_o P_o} \quad (7)$$

where $C_S/S_O P_O$ represents the slope of the oil recovery vs. slug size curve

and R_O = oil recovery as fraction of oil in place before the flood

V_S = slug volume, fraction of reservoir pore volume

C_S = cost of injected microemulsion slug

S_O = average oil saturation before flooding

P_O = price received for oil after royalties.

The point where the tangent having a slope $C_S/S_O P_O$ touches the oil recovery vs. slug size curve represents the most profitable slug size (Fig. 15). The intercept of the tangent with the ordinate represents the net oil recovery after subtracting slug costs. It can be seen from Fig. 15 that the greater the slope, $C_S/S_O P_O$, the higher the slug cost and the lower the net oil recovery. If the slope of the tangent is greater than the slope of any portion of the oil recovery-slug size curve the process will not be economically feasible. Though this technique is very quick and convenient to determine the optimum slug size for an economically feasible process, other economic factors, such as time value, sometimes make the process uneconomical.

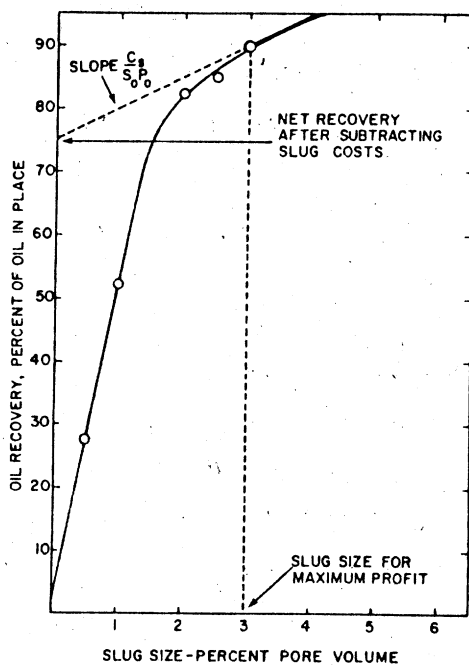


Fig. 15. The determination of most profitable slug size for tertiary oil recovery. Reproduced from Jones (28), courtesy of the Society of Petroleum Institute of A.I.M.E.

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