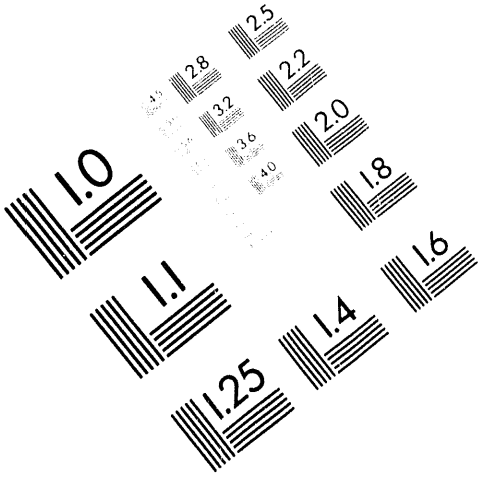


AIIM

Association for Information and Image Management

1100 Wayne Avenue, Suite 1100
Silver Spring, Maryland 20910

301/587-8202

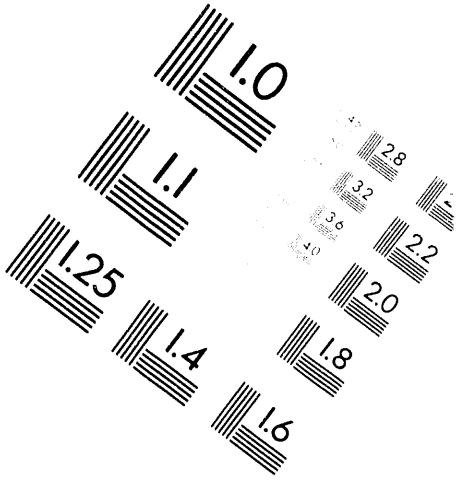
Centimeter

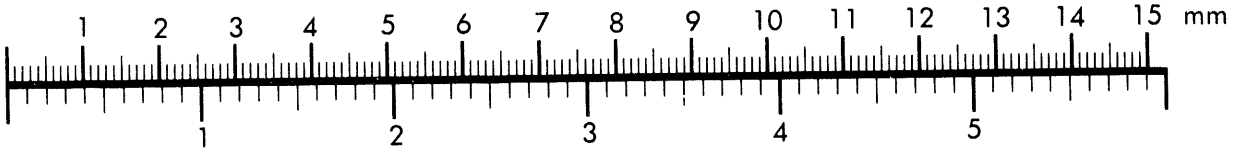
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 mm

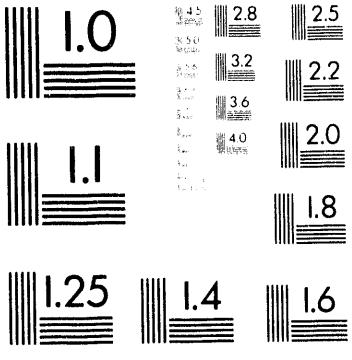
1 2 3 4 5

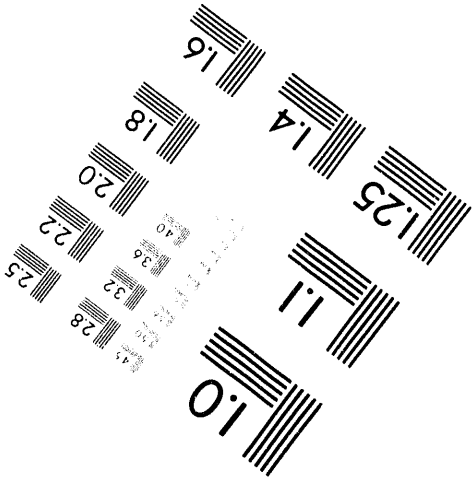
Inches

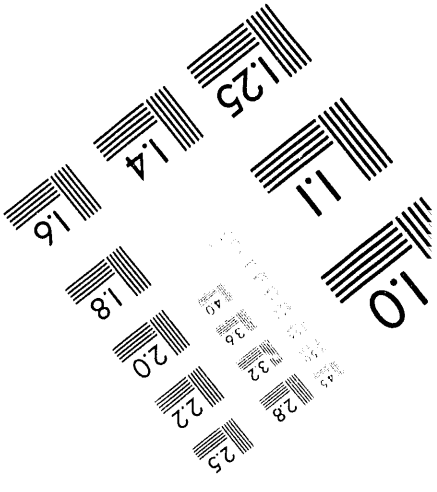
MANUFACTURED TO AIIM STANDARDS
BY APPLIED IMAGE, INC.











1 of 1

DOE/BC/14852--7

SCALE-UP OF MISCIBLE FLOOD PROCESSES FOR HETEROGENEOUS RESERVOIRS

QUARTERLY REPORT
(1 January - 31 March 1994)

Petroleum Engineering Department
Stanford University
Stanford, California 94305-2220

Prepared for the U.S. Department of Energy
Under Grant No. DE-FG22-92BC14852

Franklin M. Orr, Jr., Principal Investigator
April 1994

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

RECEIVED
USDOE/PETC
94 APR 23 AM 10: 05
ACQUISITION & ASSISTANCE DIV.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

MASTER

Introduction

The current project is a systematic research effort aimed at quantifying relationships between process mechanisms that can lead to improved recovery from gas injection processes performed in heterogeneous Class 1 and Class 2 reservoirs. It will provide a rational basis for the design of displacement processes that take advantage of crossflow due to capillary, gravity and viscous forces to offset partially the adverse effects of heterogeneity. In effect, the high permeability zones are used to deliver fluid by crossflow to zones that would otherwise be flooded only very slowly. Thus, the research effort is divided into five areas:

- Development of miscibility in multicomponent systems
- Design estimates for nearly miscible displacements
- Design of miscible floods for fractured reservoirs
- Compositional flow visualization experiments
- Simulation of near-miscible flow in heterogeneous systems

The status of the research effort in each area is reviewed briefly in the following section.

Project Status

- **Development of Miscibility in Multicomponent Systems**

  We are making progress on the creation of a systematic theory of miscibility development in multicomponent systems. The dispersion-free theory developed previously at Stanford shows that in any multicomponent displacement, the recovery behavior is determined by a small number of key tie lines that include the tie lines that extend through the initial and injection compositions, and one or more crossover tie lines. If any of those tie lines is a critical tie line, then the displacement is multicontact miscible. Thus the key to determining minimum miscibility pressure (or minimum enrichment for miscibility) is to find which tie line approaches the critical locus first as pressure (or enrichment) is increased. Graduate student Bruno Aleonard is currently investigating efficient algorithms for calculation of the critical locus. The next step is to develop an algorithm to determine which tie line lies closest to the critical locus. Once the key tie line for miscibility is so identified, it should be possible to develop an efficient algorithm to determine minimum miscibility pressure for a multicomponent system. Ph.D. student Yun Wang has joined the research group to work on theory for systems with more than four components. Our goal is to develop a mathematical technique that will allow to solve dispersion-free flow problems for systems with an abitrary number of components.

- **Design Estimates for Nearly Miscible Displacements**

  The scaling theory developed last year has been extended to include the effects of layer ordering in scaling nearly miscible displacements in layered reservoirs. We found,

as others have, that gravity forces can offset the adverse effects of high permeability channels in some layered reservoirs if adequate vertical communication exists, a result that agrees with observations obtained in our visualization experiments [24].

We have also studied the combined effects of gravity and viscous forces on residual oil saturations. Those results are reported in detail in the research result section below.

- **Design of Miscible Floods for Fractured Reservoirs**

  We have finished our first stage of modifying the existing high pressure PVT equipment to conduct high pressure gravity drainage experiments. In the first experiment, now underway, we used Means crude, whose phase behavior with CO_2 has been well studied in our laboratory [10]. A 2-ft long and 2.5-in diameter sandstone core was saturated with 0.73 pore volume (PV) of crude oil and 0.27 PV of water, before it was surrounded with liquid CO_2 at 900 psi and room temperature (about 22°C). Preliminary results show that gravity drainage is rather efficient even at fairly low pressure (900 psi). We are in the process of systematically studying gravity drainage in a pressure range from 900 psi to 1500 psi, in order to investigate the effects of miscibility development and consequent changes in interfacial tension on gravity drainage rates and final oil recovery.

  In this area, we have also made progress in developing a theory of three phase gravity drainage. Recent experimental and theoretical results suggest that we can obtain zero residual oil saturation in some parts of a reservoir, if the reservoir is water-wet and the system has a positive spreading coefficient [3].

- **Flow Visualization Experiments**

  To understand more fully the visualization experimental results we have obtained, we are in the process of modifying a compositional simulator code to simulate the experiments. A subroutine for calculating the phase behavior of the fluid system used in our experiments is being written. The oil-water-alcohol systems used in the low pressure experiments are not modeled accurately by cubic equations of state, and hence an approach based on excess free energy models is being used.

- **Simulation of Flow in Heterogeneous Reservoirs**

  We have continued to investigate the streamtube approach as a numerical alternative to conventional finite difference simulators to be used in predicting near-miscible gas injection in heterogeneous reservoirs. We have applied the streamtube approach to the two-phase immiscible case which is assumed to be well understood and for which many reliable numerical methods have been developed. Our results have given us new insight on the applicability of the streamtube approach and, particularly, on the novel idea that proposes to map a one-dimensional analytical solution (Riemann solution) along the streamtubes to obtain a two-dimensional solution for a heterogeneous reservoir [20].

  Hamdi Tchelepi, a Ph.D student, has finished his dissertation titled "Viscous fingering, gravity segregation and permeability heterogeneity in two-dimensional and three-dimensional flows". He concluded that gravity could play a very important role defining fluid distributions of flow in heterogeneous reservoirs. He also found that when gravity, heterogeneity and viscous instability are of comparable importance, two-dimensional flows are significantly different from three-dimensional flows.

Research Results

In this section, we report in detail our recent results from a study of the combined effects of gravity and viscous forces on residual oil saturation.

Introduction

Tertiary oil recovery or aquifer remediation processes attempt to recovery oil that is trapped by capillary forces. Displacement of a hydrocarbon phase by water alone is an immiscible displacement that cannot comletely recovery oil from reservoirs due to the interplay of capillary forces with heterogeneities of the media. Two types of heterogeneities are commonly dealt with: pore-level heterogeneity and macroscopic heterogeneity. Pore-level heterogeneity, such as pore size (grain size) and pore structure variations, controls the amount of oil left after the injected fluid has swept a zone, whereas macroscopic heterogeneity determines zones that the injected fluid sweeps. In numerical simulation of a displacement process, macroscopic heterogeneity can be represented directly by assigning different rock properties (permeability and porosity) to certain grid blocks, given knowledge of the detailed structure of the medium. Because of the complex nature of pore entrapment mechanisms, however, the effects of pore level heterogeneity are represented by empirical correlations. One of the empirical correlations is the capillary desaturation curve (CDC), which defines the relationship of the residual oil saturation and the physical properties of a system. Accurate representation of the dependence of the CDC on fluid and rock properties is of great importance for simulations of enhanced oil recovery and spilled oil clean-up processes, because these processes must reduce the residual oil saturation to relatively low levels. This work describes theory and experiments that demonstrate the relative contributions of gravity, viscous and capillary forces in the correlation of residual oil saturation and the physical properties of water-wet systems.

The physical properties of a system are commonly represented by a capillary number, which is usually defined by one of the following equations

$$N_{c1} = \frac{\mu_w v}{\sigma}, \tag{1}$$

or

$$N_{c2} = \frac{\nabla p k}{\sigma}, \tag{2}$$

and a Bond number defined by

$$N_B = \frac{\Delta \rho g k}{\sigma}, \tag{3}$$

or

$$B = \frac{\Delta \rho g R^2}{\sigma}, \tag{4}$$

where μ_w is the viscosity of the displacing phase, v is Darcy velocity, ∇p is the pressure gradient, k is permeability, R is the radius of the grains composing the porous medium, $\Delta\rho$ is the density differences between the fluids, and σ is the interfacial tension (IFT) of the system. According to Darcy's law, the capillary numbers (N_{c1} and N_{c2}) are related

by $N_{c2} = N_{c1}/k_{rw}$, where k_{rw} is the relative permeability of the displacing phase. The use of N_{c1} or N_{c2} in the literature depends on the application to specific situations. N_{c1}, for example, is likely to be used to correlate results of experiments with constant injection rates, whereas N_{c2} may be used to describe flows with constant pressure drop. In this work, however, we find that even for processes with constant injection rates, N_{c2} is a more appropriate form to represent the ratio of viscous forces to capillary forces. The Bond numbers B and N_B are related by the correlation of the permeability (k) and the grain sizes (R) of a medium.

There are two CDC's for a displacement system, depending on the continuity of the displaced fluid [12, 15, 23]. A discontinuous nonwetting phase is more difficult to displace from a medium than a continuous nonwetting phase [12, 15]. In this work, we focus our attention on the displacement of continuous nonwetting phase from a porous medium, which is commonly involved in oil recovery processes with a oil bank. CDC's are generally obtained from laboratory measurements[8, 11, 15, 19], although attempts have been made to predict CDC's by statistical [13] or deterministic theories [12, 18, 23]. Studies of CDC's have been largely focused on the balance of capillary and viscous forces [12, 17, 18], which is measured by the capillary number. Consequently, gravity effects are neglected in CDCs used in most simulators of enhanced oil recobery processes, even though some studies [15, 21, 22] have shown that gravity effects can be significant. In this work, we examine the combined effects of gravity and viscous forces on oil entrapment in porous media, and we define conditions under which gravity forces can be neglected or must be included in the analysis.

Entrapment mechanisms

In order to identify the factors that influence oil entrapment during immiscible displacements, we first review entrapment mechanisms. Mohanty *et al.* [14] investigated the physics of oil entrapment in water-wet media, and identified two entirely different entrapment mechanisms, namely, a snap-off process that traps oil in a pore and a by-pass process caused by competition of flows between pores. Using detailed experimental observations, Chatzis *et al.* [4] determined that approximately 80 percent of oil is entrapped by snap-off processes and 20 percent by by-passing processes for consolidated, water-wet media.

Snap-off occurs in pores with large aspect ratios, the ratio of pore body and pore throat diameters. The large aspect ratio creates a significant lower wetting phase pressure at the pore throat than that in the pore body. Hence, the wetting phase flows towards the pore throat, and foms a collar that grows and eventually breaks the nonwetting phase. Roof [17] derived a static criterion for snap-off in noncircular capillary tubes, based on the capillary force balance at the pore throat and the pore body. A noncircular capillary tube was used as a model of the irregularities of pores and the roughness of solid surface of the medium. Ransohoff *et al.* [16] extended Roof's static analysis to include the effects of viscous flow resistence in the water filled corners of the capillary tube. For a system shown in Fig. 1A, they obtained the static criterion for snap-off,

$$R_T \geq \frac{C_m R_c R_\lambda(0)}{R_\lambda(0) - R_c}, \tag{5}$$

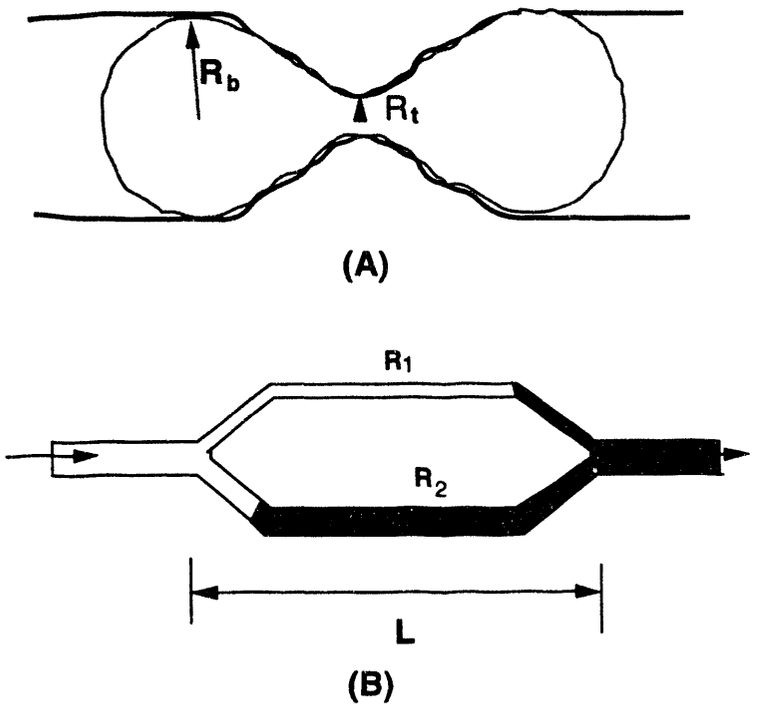


Figure 1: Commonly used snap-off model(A) and pore Doublet model (B).

where C_m is a dimensionless interfacial curvature, which is a function of the cross-sectional geometries, and R_c and $R_\lambda(0)$ are the pore throat and pore body diameters respectively.

To include the dynamic effects of viscous flow, Ransohoff *et al.* [16] and Gauglitz *et al.* [9] calculated and experimentally measured the time required to transport enough fluid into the pore throat to have snap-off, and compared it to the time for the nonwetting phase to flow through the pore throat. The ratio of these two times indicates whether snap-off can occur for a given system.

The random nature of the sizes and locations of pores in porous media incorporating the interconnections among the pores generates flow competitions among pores. The displacing fluid in the fast flow pores can trap oil in pores in which flows are slow. This mechanism is referred to as by-passing. Pore doublet models (PDM) have been used both theoretically [4, 12] and experimentally [4] to demonstrate the by-pass mechanism. The PDM is based on the assumpation that well-developed-Poiseuille flows compete in two parallel flow paths (pores) with different sizes (see Fig. 1B). The flow velocity in each flow path can be obtained by combining Poiseuille's law and the Young-Laplace equation [12]. The ratio of the velocities is an indication of the amount of fluid trapped in one pore. For an imbibition process, capillary forces draw the displacing phase into the smaller pore, while viscous forces make the fluid flow more rapid in the larger pore. The result of this competition is that at low injection rate, the oil in the large pore would be trapped. Chatzis and Dullien [4] found experimentally, however, that little oil was trapped in their PDM's during free imbibitions. That might be because that capillary forces controlled the flow processes in their free imbibitions, and that

curvatures at the conjunctions were larger than that of either tube. In reality, pores in the medium are not perfect capillary tubes, but are irregularly-shaped and by-passing can cause entrapment. Chatzis and Dullien's observations [4] from the combined model of capillary tube and neck-bulge-neck pore indicate that there oil can be trapped by the by-passing process.

By-passing processes can also be represented by network models for studies of entrapment mechanisms in porous media [2, 5, 6, 7, 21, 23]. Network models represent porous media by networks of pores with different sizes and connectivities. Another approach, percolation theory, has also been used to represent the random nature of the porous media, in which the flow path is fully random. In its original form, percolation theory represented only two-phase displacements when capillary forces dominate the flow process, but it did not account for viscous or gravity forces. Invasion percolation theory was then introduced to include both the randomness of the medium and the continuity of the fluids. In the following subsection, we review briefly effects of gravity in invasion percolation theory as well as the experimental results that demonstrate effects of gravity on residual nonwetting phase saturation.

Gravity Effects on Entrapment

The first theoretical investigation of gravity effects was reported by Wilkinson in an invasion percolation study [21]. Wilkinson neglected the snap-off process, and assumed that the nonwetting phase is entrapped by by-passing process only. Correlation lengths for both viscous and buoyancy forces were introduced to measure the relative magnitudes of viscous and buoyancy forces compared with capillary forces in the medium. A viscous correlation length was defined as

$$\xi_V = \left(\frac{L_{max}}{R}\right)_V \propto \left(\frac{N_{c1}}{k_w}\right)^{-\upsilon/(1+\upsilon)}, \tag{6}$$

where L_{max} is the maximum length of oil clusters in the system, R is the grain size (radius) of the medium, $k_w = kk_{rw}/R^2$ and υ is a percolation exponent ($\upsilon = 0.88$ for three dimensional percolation). They also defined a gravity correlation length (ξ_G),

$$\xi_G = \left(\frac{L_{max}}{R}\right)_G \propto B^{-\upsilon/(1+\upsilon)}, \tag{7}$$

where B is the Bond number [15, 21]. For gravity-dominated flow, the residual oil saturation S_{or} was related to the gravity correlation length by

$$S^*_{or} - S_{or} \propto \left(\frac{1}{\xi_G}\right)^{(1+\beta)/\upsilon} \propto B^{\lambda}, \tag{8}$$

where $\lambda = (1+\beta)/(1+\upsilon)$, which is a percolation constant ($\lambda = 0.77$ for three dimensional percolation), S^*_{or} is the residual oil saturation at very low capillary number and Bond number, and β is also a percolation constant of 0.45 for three dimensional percolation. For viscous-dominated cases, the residual oil saturation was correlated as

$$S^*_{or} - S_{or} \propto \left(\frac{1}{\xi_V}\right)^{(1+\beta)/\upsilon} \propto \left(\frac{N_{c1}}{k_w}\right)^{\lambda}. \tag{9}$$

For situation in which both viscous and gravity forces act, Wilkinson [21] assumed that capillary and gravity forces were additive, and that the residual oil saturation depends on $N_{c1} + (Bkk_{rw}/R^2)$.

Blunt *et al.* [2] used an effective correlation length for cases in which both viscous and gravity forces were involved. They defined the effective correlation length as

$$\frac{1}{\xi} = \frac{1}{L} + \frac{1}{\xi_V} + \frac{1}{\xi_G}, \tag{10}$$

where L is the length of the system. For a porous medium of relatively large size, $1/L \approx 0$, and hence

$$\frac{1}{\xi} \approx \frac{1}{\xi_V} + \frac{1}{\xi_G}. \tag{11}$$

In terms of capillary and Bond numbers, the residual nonwetting phase saturation is

$$S_{or}^* - S_{or} \propto \left((Bk_{rw})^{\upsilon/(1+\upsilon)} + N_c^{\upsilon/(1+\upsilon)}\right)^{(1+\beta)/\beta}. \tag{12}$$

Eq. 12 indicates that the effective correlation length theory does not give a linear combination. However, with the percolation constants, the nonlinearity of Eq. 12 is weak.

An experimental study of gravity effects on residual oil saturation was conducted by Morrow and Songkran [15]. They reported a substantial effect of gravity on residual nonwetting phase saturation in glass-bead packs. They used beads with different diameters to obtain a wide variation of Bond numbers. In all displacements, interfacial tension (IFT) remained constant. The capillary number was varied by changing injection rates. They correlated their results against a linear combination of N_{c1} and B,

$$S_{or} = f(N_{c1} + 0.001413B). \tag{13}$$

This correlation agrees well with Wilkinson's results, although Wilkinson's theory neglected the snap-off process. Blunt *et al.* [2] demonstrated numerically that gravity forces (represented by the Bond number B) behave the same as viscous forces (N_{c2}). However, they did not obtain a linear combination of the two numbers. In the following sections, we demonstrate theoretically and experimentally that a linear combination of the dimensionless groups that represent capillary, viscous and gravity forces gives an accurate correlation of the capillary desaturation curve.

Extended REV-Scale Models

Previously available models of snap-off and by-passing neglect the influence of gravity. In this section we extend such models to include gravity. In the following derivation of equations, we assume that the interface between oil and water phases is always in equilibrium, so that we can use the Young-Laplace equation to represent the pressure difference across an interface. Flow of both phases is assumed to be well-developed Poiseuille flow, and therefore, Poiseuille's law or Darcy's law is used to represent viscous pressure drops.

Snap-off Model

In past studies of snap-off processes, oil blob sizes were assumed to be smaller than the pore size. That assumption is known to be violated in displacements in real porous media. For example, Chatzis [4] observed the blobs could be several pore sizes in extent. In our analysis, we consider an oil blob occupying two pores in the vertical direction (see Fig. 2B). However, the analysis is not limited to two-pore lengths and could be easily extended to multipore arrangements. Consider the situation shown in Fig. 2B. The pressures in both phases at the pore throat are

$$P_o = P_i + \frac{C_m \sigma}{R_b} - \Delta P_{ov} - \rho_o g L, \tag{14}$$

and

$$P_w = P_i - \Delta P_{wv} - \rho_w g L, \tag{15}$$

where R_b is the pore body radius, C_m is the dimensionless interfacial curvature in the pore body and ΔP_{ov} and ΔP_{wv} are the viscous pressure drops of the oil and the wetting phase. Because of the continuity of the wetting phase, the wetting phase can reach the pore throat through other neighboring pores. Therefore, we use Darcy's law to calculate the viscous pressure drops for both phases. ΔP_{ov} and ΔP_{wv} are then expressed as $\Delta P_{ws} = (\mu_w v L)/(k k_{rw})$, and $\Delta P_{ov} = (\mu_o v_o L)/(k k_{ro})$. Thus, the pressure difference between the two phases at the pore throat is

$$\Delta P_1 = (P_o - P_w)_1 = \frac{C_m \sigma}{R_b} + (\rho_w - \rho_o) g L + \frac{\mu_w v L}{k k_{rw}} - \frac{\mu_o v_o L}{k k_{ro}}. \tag{16}$$

At the pore throat, we cal also obtain the pressure difference between the two phases from the Young-Laplace equation,

$$\Delta P_2 = (P_o - P_w)_2 = \frac{\sigma}{R_t} - \frac{\sigma}{R_o}, \tag{17}$$

where R_t is the pore throat radius, and R_o is the radius of the pore neck.

Now we consider the following situations: $\Delta P_2 > \Delta P_1$ and $\Delta P_2 < \Delta P_1$. When $\Delta P_2 > \Delta P_1$, the fluids would flow in such a way as to reduce ΔP_2 to keep the two forces in balance. In order to decrease ΔP_2, the system would either increase R_t or decrease R_o. It is impossible to increase R_t further, because of the solid pore structure. Thus, the system would reduce R_o. To reduce the value of R_o, capillary forces pump the wetting phase into the pore throat. Consequently, a wetting phase collar ring would forms at the pore throat [16]. The formation of the collar ring reduces the value of R_t, and results in snap-off. However, when $\Delta P_2 < \Delta P_1$, the system becomes stable. In order to balance the pressure difference in this case, the system would either reduce R_t or increase R_o. Reducing R_t is impossible, because the viscous pressure difference ΔP_1 push the interface outward to increase R_t. Thus, increasing the effective value of R_o is the only solution. To increase the effective value of R_o, the capillary forces push the wetting phase away from the pore throat and there is little wetting phase at the pore throat. Therefore, there would be no snap-off. In summary, we argue that the system would be stable if $\Delta P_2 < \Delta P_1$. We then obtain the following stability condition,

$$N_{c1} + \frac{k_{rw}}{a} N_B > \frac{k k_{rw}}{R_t L a} \left(1 - \frac{R_t}{R_o} - \frac{C_m R_t}{R_b}\right), \tag{18}$$

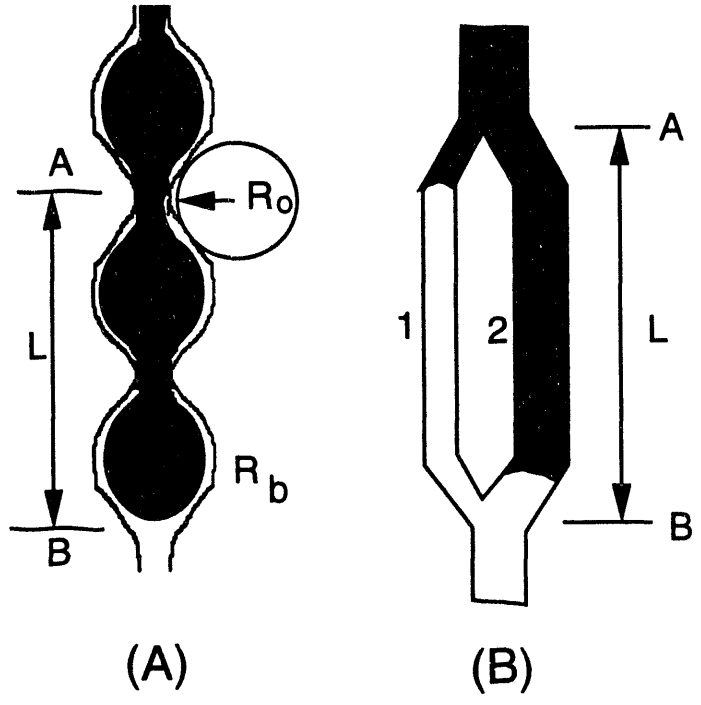


Figure 2: Vertically oriented snap-off model (A) and pore doublet model (B).

where $a = v_w/v_t - Mv_o/v_t$, v_t is the total flow velocity, and M is the mobility ratio at the trailing edge of the displacement front, $M = \mu_o k_{rw}/\mu_w k_{ro}$. We define the Bond number (N_B) here in terms of permeability, because permeability is the directly measurable property of the medium. Eq. 18 shows that a linear combination of the capillary and Bond numbers arises naturally from a simple physical picture of a snap-off process. The relative magnitudes of gravity and viscous forces depend on values of the wetting phase relative permeability and the constant a. To estimate the value of a, we consider the situation at the moment just before a drop of oil is trapped in the pores. We assume that the nonwetting phase flows much more slowly than the wetting phase, so that, $v_w >> v_o$. Therefore, $v_w \approx v_t$, and the value of a is close to one. Hence the wetting phase relative permeability determines the relative contribution of the capillary and the Bond numbers, and

$$N_{c1} + k_{rw}N_B > k_{rw}\frac{k}{R_t L}(1 - \frac{R_t}{R_o} - \frac{C_m R_t}{R_b}). \tag{19}$$

Eq. 19 suggests that mobility ratio would have minimal effect on the final residual nonwetting phase saturation, which agrees with experimental observations [1, 19].

If we set $N_{c1} = 0$ and $N_B = 0$, Eq. 19 simplifies to

$$R_b > \frac{C_m R_t R_o}{R_o - R_t}, \tag{20}$$

which is the same as Eq. 5.

Doublet Model

For vertically oriented doublet pores as Fig. 2B shows, we write down the pressure drops from point A to point B for each pore as (on the assuption that the tubes are cylindrical)

$$\Delta p_1 = \frac{8\mu_w v_1 L_1}{R_1^2} + \frac{8\mu_o v_1 (L - L_1)}{R_1^2} - \frac{2\sigma}{R_1} + L_1 \rho_w g + (L - L_1)\rho_o g, \tag{21}$$

and

$$\Delta p_2 = \frac{8\mu_w v_2 L_2}{R_2^2} + \frac{8\mu_o v_2 (L - L_2)}{R_2^2} - \frac{2\sigma}{R_2} + L_2 \rho_w g + (L - L_2)\rho_o g, \tag{22}$$

where R_i is the radius of tube i, and L_i is the distance the displacing fluid flows in tube i, L is the length of the tubes, and v_i is the flow velocity in tube i. Since the two pores are parallel, the pressure drops Δp_1 and Δp_2 must be equal, $\Delta p_1 = \Delta p_2$. Therefore, we obtain the following expression in which the average velocity (v_a) of the doublet pores is $v_a = (R_1^2 v_1 + R_2^2 v_2)/(R_1^2 + R_2^2)$.

$$N_c m + (l_1 - l_2)\frac{f}{1+f} N_B = \frac{2k}{R_1 L}\frac{f}{1+f}(1 - \frac{R_1}{R_2}), \tag{23}$$

where $l_i = L_i/L$, $\mu_r = \mu_o/\mu_w$, $f = R_2^2/R_1^2$, and

$$m = (1 - \mu_r)\left((1 + f - \frac{v_2}{v_a} f) l_1 f - \frac{v_2}{v_a} l_2\right) + \mu_r \left(f(1 + f - \frac{v_2}{v_a}) - \frac{v_2}{v_a}\right). \tag{24}$$

The permeability of the PDM is defined as $(R_1^2 + R_2^2)/8$ from Poiseuille's law.

To simplify the arguments, we assume the radius of pore 1 is smaller than that of pore 2, $R_1 < R_2$. Capillary forces draw the wetting phase into the smaller pore (pore 1), and viscous forces make fluid flow more easily in the larger pore (pore 2). At the same time, gravity forces reduce the velocity difference between pores. Reduction of viscous forces slows the flow in the larger pore, and results in more oil trapped in the larger pore. If the oil in pore 2 were completely trapped, we would have the following parameters: $v_2 = 0$, $l_1 = 1$ and $l_2 = 0$, and $m = f(1 + f)$. To avoid entrapment of the nonwetting phase in pore 2 completely, therefore, the system must have a value of m smaller than $f(1 + f)$. Thus, rearrangement of Eq. 23 gives

$$N_{c1} + C N_B > C \frac{2k}{R_1 L}(1 - \frac{R_1}{R_2}), \tag{25}$$

where $C = 1/(1 + f)^2$.

For a given system, Eq. 25 indicates that the combined effects of gravity and capillary forces must be greater than a certain value to avoid oil entrapment in doublet pores. The relative magnitude of gravity forces and viscous forces depends on the value of C, which represents the heterogeneity of the system. $C = R_1^4/(R_1^2 + R_2^2)^2$ is the relative permeability of the displacing phase (the wetting phase), and can be derived as following,

$$C = \frac{R^4}{(R_1^2 + R_2^2)^2} = \frac{k_1 R_1^2}{k(R_1^2 + R_2^2)} = \frac{Q_1}{Q_t}, \tag{26}$$

where Q_1 and Q_t are the flow rate in pore 1 and the total flow rate in both pores. According to Darcy's law, $Q_1 = (Ak_{rw}k/\partial\Phi/\partial l)/\mu$, and $Q_t = (Ak/\partial\Phi/\partial l)/\mu$ for a given flow area A and potential gradient $\partial\Phi/\partial l$. Therefore,

$$C = \frac{Q_1}{Q_t} = \frac{\frac{Akk_{rw}}{\mu}\frac{\partial\Phi}{\partial l}}{\frac{Ak}{\mu}\frac{\partial\Phi}{\partial l}} = k_{rw}, \tag{27}$$

and

$$N_{c1} + k_{rw}N_B > k_{rw}\frac{2k}{R_1 L}(1 - \frac{R_1}{R_2}). \tag{28}$$

Thus, Eq. 28 also suggests that a linear combination of the capillary and Bond numbers can be used to state a criterion for by-passing. Here again, the coefficient of the Bond number is the wetting-phase relative permeability.

Summary

In both snap-off and doublet models, we obtain critera for prevention of nonwetting phase entrapment in porous media in terms of linear combinations of capillary and Bond numbers. Comparison of Eqs. 19 and 28 indicates that they have similar forms. In both cases, the relative contributions of capillary and Bond numbers are determined by the relative permeability of the displacing phase. Using the relationship of N_{c1} and N_{c2}, we obtain the following equations for snap-off and by-pass processes.

$$N_{c2} + N_B > \frac{k}{R_t L}(1 - \frac{R_t}{R_o} - \frac{2R_t}{R_b}), \tag{29}$$

and

$$N_{c2} + N_B > \frac{2k}{R_1 L}(1 - \frac{R_1}{R_2}). \tag{30}$$

The simplicity of Eqs. 29 and 30 suggests that N_{c2} is a more appropriate definition of capillary number than N_{c1} even for processes with constant injection rates.

Experiments

Morrow and Songkran's experiments [15] provide some evidence that a linear combination of capillary number and Bond number determines residual oil saturation. In their experiments, however, the Bond number was changed by varying the sizes of the beads used in packing their columns. We now investigate whether use of the linear combination is reasonable if we change Bond number by the variation of IFT and density differences of the fluids. In this section, we report results from experiments designed to examine these parameters.

All displacements were conducted in the same sand-pack column. The Bond number was varied by using different IFT's and density differences of the fluids. Fig. 3 is a schematic of the experimental apparatus. The HPLC pump provided constant injection rates ranging from 0.1 to 8.0 cc/min. The length of the sand-packed porous medium was 119.0 cm and the diameter 1.95 cm. The permeability was 48.5 Darcy and the

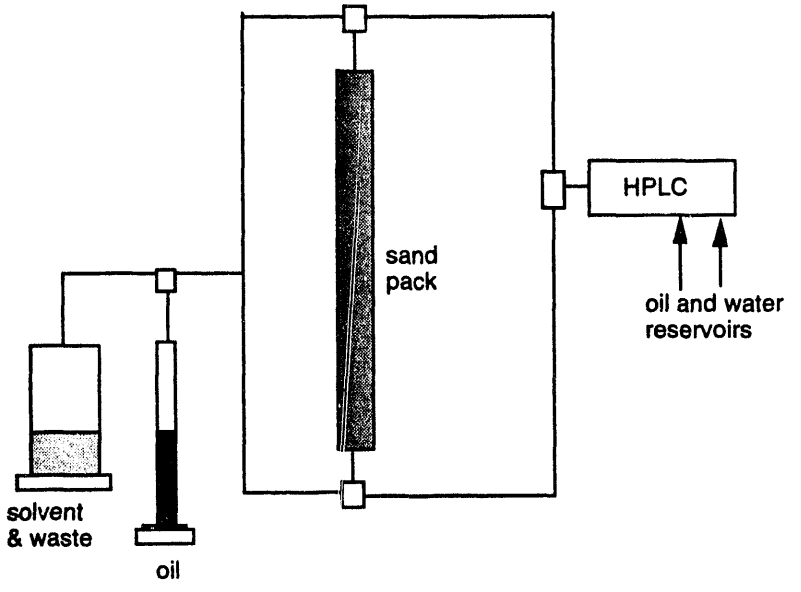


Figure 3: A schematic diagram of the experimental setup.

porosity, 0.256. We used mixture of brine, iso-octane (iC_8) and isopropanol (IPA) to generate fluid pairs of wide range of IFT and densities differences, This system has been well studied [15]. Four tie-lines were used to obtain IFTs varying from 0.1 to 38.1 mN/m and densities from 0.11 to 0.33 g/cc, which correspond to a range of capillary and Bond numbers from 10^{-6} to 10^{-3} in this work.

All displacements were conducted with initial wetting phase saturations. They established by injecting the nonwetting phase into the top of the column that was fully saturated with the wetting phase. The initial wetting phase saturation varied from 0.15 to 0.25 of pore volume. The large variation of initial wetting phase saturations were results of large variations in mobility ratios in different runs. In this range of initial wetting phase saturation, repeated experiments showed that this variation of initial wetting phase saturation did not influence the residual nonwetting phase saturation. Therefore, the differences in the residual nonwetting phase saturation are the results of the capillary and Bond number variations. To study the directional effects of gravity forces, we conducted displacements by injecting the wetting phase from either bottom or top of the column. We refer to displacement from the bottom as gravity-favorable and that from the top as gravity-unfavorable, because the gravity forces stabilize the displacements when injected phase enters the column from the bottom.

In all the displacements, we observed little additional recovery shortly after breakthrough, an observation that is consistent with the idea that the sand-pack was strongly-water wet. Following the common practice, we plot the final residual oil saturation against the capillary number alone for all displacements in Fig. 4. Apparently, the experimental data cannot be reasonably correlated by the capillary number alone. The experimental results also indicate, therefore, that gravity forces and the flow directions affect the residual nonwetting phase saturations.

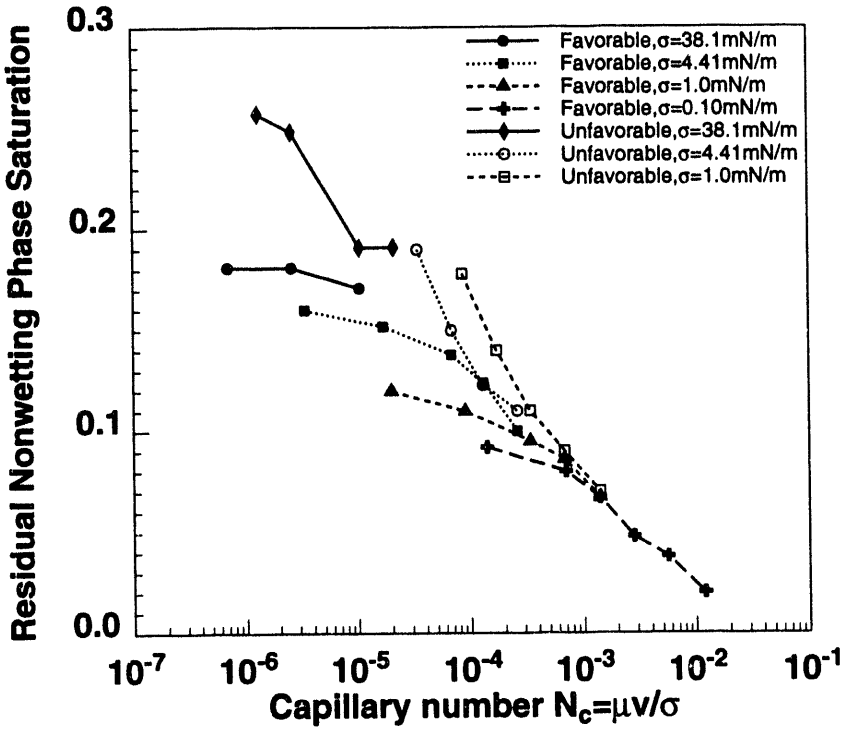


Figure 4: The Correlations of residual nonwetting phase saturation with the capillary number alone for all displacements.

Discussion

In the definitions of capillary number (N_{c1}) and Bond number N_B, five variables are involved: the injection rates (v), the IFT (σ), the density difference ($\Delta\rho$), the viscosity of the wetting phase (μ_w), and the permeability of the medium (kk_{rw}). In the experiments described in the previous section, we varied IFT and density differences, and injection rates to obtain a wide range of capillary and Bond numbers. To check the other parameters, we review the experimental results of Morrow and Songkran, who varied the capillary number and Bond number by changing different bead sizes and injection rates. Changing bead size changes the permeability of the bead pack. The permeability of a beadpack can be related to the bead size through the Kozeny-Carman equation

$$k = \frac{\phi^3}{k_z(1-\phi)^2 A_s^2}, \tag{31}$$

where A_s is the specific surface area per unit solid volume, for spherical bead $A_s = 3/R$, K_z is the Kozeny constant, which is approximately equal to 5 for bead packings, and ϕ is the porosity of the packing, which is about 0.38 for bead packings. Therefore, the permeability of a bead pack can be simply related to bead size as

$$k = 0.00317R^2. \tag{32}$$

Thus, the correlation given by Morrow and Songkran can rearranged in terms of N_B as

$$Sor = f(N_{c1} + 0.445N_B). \tag{33}$$

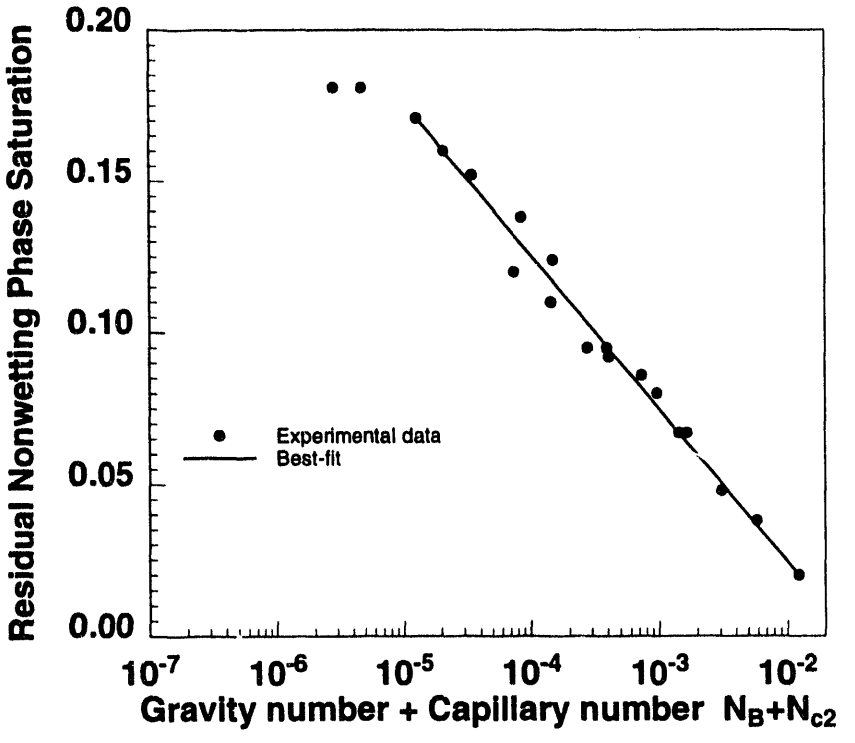


Figure 5: Correlation of the residual oil saturations and the sum of the capillary and Bond numbers for gravity-favorable displacements.

Comparison of Eq. 33 with the theoretical results indicates that the wetting phase relative permeability at the trailing edge of the displacement front is about 0.445, which is consistent with Morrow and Songkran's measurements ($k_{rw} = 0.5$).

As did Morrow and Sougkran [15], we obtained a lest-square fit of our residual oil saturations from gravity-favorable displacements with an effective number defined as $N_e = N_{c1} + cN_B$. As Fig. 5 shows, a straight-line correlation on the semi-log plot exists when $c = 0.5$ and $N_e > 10^{-5}$. The value of c_1 is the relative permeability of the wetting phase according to Eqs. 18 and 28. This value is very close to the measured relative permeability by Morrow and Songkran. Again, our experiments suggest that a linear combination of the capillary and the Bond numbers correlates the residual oil saturations, and the appropriate coefficient is the wetting phase relative permeability.

Using the same value of c, we correlated all the experimental results, as Fig. 6 shows, for both gravity-favorable and gravity-unfavorable displacements. At high values of N_e, the correlation is excellent, while it is less satisfactory when N_e is small. The difference between the gravity-favorable and -unfavorable displacements may result partly from the accuracy of the flow rate and permeability measurements, because the subtraction of the two numbers enhanced the significance of the measurement error when these two values are comparable. In general, the correlation is good and we obtain the following correlation of the residual oil saturation with the capillary and the Bond numbers, when $N_e > 10^{-5}$.

$$S_{or} = 0.02 + 0.0505 log(\frac{0.01227}{N_{c1} + 0.5N_B}). \tag{34}$$

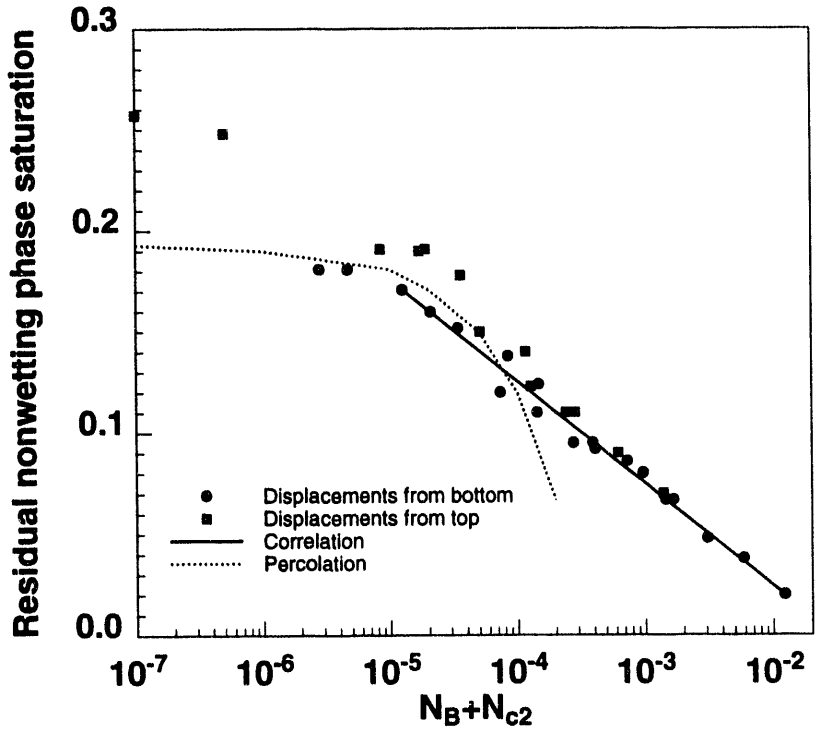


Figure 6: Correlations of Residual oil saturations and the sum of capillary and Bond numbers from percolation theory and best-fit of the experimental data.

Fig. 7 shows a comparison of the experimental data and the correlation given by Eq. 34. The agreement is very good except for gravity- unfavorable displacements at high IFT's. In these cases, the displacements were no longer stable, because the gravity forces were larger than the viscous forces, that is, the value of $N_{c1} + 0.5N_B$ is close to zero or negative. Therefore, for a system with a gravity forces larger than or equal to the capillary forces, gravity-favorable displacements have much lower residual oil saturation than do gravity-unfavorable displacements.

For a given system, it would be useful to determine which forces are most important. Therefore, we rearrange the linear combination to obtain

$$N_e = N_{c1}(1 + \frac{\Delta\rho g k k_{rw}}{\mu_w v}). \tag{35}$$

The relative magnitudes of N_{c1} and N_B in a system can be reflected by the gravity number

$$N_g = \frac{\Delta\rho g k k_{rw}}{\mu_w v}. \tag{36}$$

When $N_g > 1$, the Bond number is the dominating factor, wheresas when $N_g < 1$, capillary number is the controlling parameter in determining the residual oil saturation.

We should note that the gravity number (N_g)is proportional to the medium permeability. Thus, flow in a high-permeablity medium will have larger gravity effects than that in a low-permeability medium. To illustrate this concept, let us compare typical oil-spill and an oil recovery situations. The permeability of a typical soil is about 100

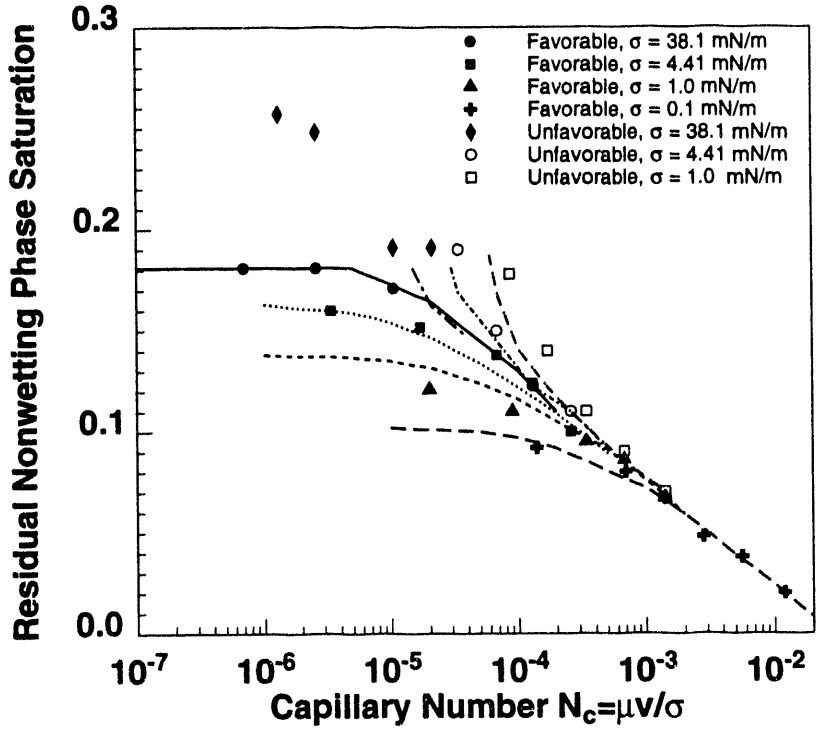


Figure 7: Comparison of the correlation given by Eq. 35 with experimental data. Lines are correlations and dotes are the experimental data.

darcy, water viscosity is around $10^{-3} N * s$ (1 cp), and the flow rate is about 1 ft/day, which is about 3.5 x $10^{-6} m/s$. We also assume that the density difference is about $300 kg/m^3$ and the IFT is about 40 x $10^{-3} N/m$. The gravity number (N_g) is about 5, that is, the gravity forces is larger than the viscous forces in typical spilled-oil clean-up processes. For a waterflood oil recovery process, however, the permeability is in the order of 100 md. If we used the same fluid properties, the gravity number is about 5×10^{-3}. Thus, gravity forces are less significant than viscous forces in determining final oil saturation in oil reservoirs.

From our results, we can also make an argument on the concept of effective correlation length used by Blunt *et al.* [2]. The criterion for preventing oil entrapment is

$$N_e > \frac{a}{L} \tag{37}$$

where a is the parameter representing the heterogeneity of the medium, and L is the length of the oil ganglion to be trapped. Therefore, the length of an oil ganglion to be trapped in the system is

$$L \propto \frac{a}{N_e} = \frac{a}{N_{c2} + N_B}. \tag{38}$$

By the same argument given by Blunt *et al.* [2], we obtain

$$\xi_e \propto N_e^{-\upsilon/(1+\upsilon)} \tag{39}$$

and

$$S_{or}^{*} - S_{or} \propto \left(\frac{1}{\xi_e}\right)^{(1+\beta)/\upsilon} \propto N_e^{\lambda} = (N_{c2} + N_B)^{\lambda} \tag{40}$$

where ξ_e is the effective correlation length. Thus, gravity and viscous forces have similar effects on effective correlation length of a displacements process. Fig. 6 is a comparison of the experimental data and the invasion percolation correlation. As one expects, the agreements become less satisfactory at high value of N_e, because that percolation is valid only for cases in which capillary forces dominate.

Conclusions

From this work, we can make the following conclusions:

1. We demonstrated theoretically and experimentally that a linear combination of gravity and viscous forces can be used to correlate residual nonwetting phase saturations for both gravity-favorable and gravity-unfavorable displacements.

2. When gravity forces are comparable to or larger than the viscous forces, gravity-unfavorable displacements have significantly higher residual nonwetting phase saturation than gravity-favorable displacements.

3. Because soils have much higher permeabilities than oil reservoirs, gravity effects on residual nonwetting phase saturations are much more significant in spilled-oil clean-up than in oil recovery processes.

4. The effective correlation length for a percolation process can be related to a linear combination of the gravity and viscous forces.

References

[1] Abrams, A.: "The Influence of Fluid Viscosity, Interfacial Tension, and Flow Velocity on Residual Oil Saturation Left by Waterflood," *Soc. Pet. Eng. J.* (1975) **14**, 927–935.

[2] Blunt, M., King, M.J. and Scher, H.: "Simulation and Theory of Two-Phase Flow in Porous Media," *Phys. Rev. A* (1992) **46**, No. 12, 7680–7698.

[3] Blunt, M.J., Fenwick, D. and Zhou, D.: "What Determines Residual Oil Saturation in Three Phase Flow?," paper SPE 27816 presented at the 1994 Ninth Symposium on Improved Oil Recovery, Tulas, OK, April.

[4] Chatzis, I. and Morrow, N.R.: "Correlation of Capillary Number Relationships for Sandstone," *Soc. Pet. Eng. J.* (October 1984) **5**, 555–562.

[5] Fatt, I.: "The Network Model of Porous Media I: Capillary Pressure Characteristics," *Petr. Trans., AIME* (1956) **207**, 144–159.

[6] Fatt, I.: "The Network Model of Porous Media II: Dynamic Properties of a Single Size Tube Network," *Petr. Trans., AIME* (1956) **207**, 160–163.

[7] Fatt, I.: "The Network Model of Porous Media III: Dynamic Properties of Networks with Tube Radius Distribution," *Petr. Trans., AIME* (1956) **207**, 164–170.

[8] Garnes, J.M., Mathisen, A.M., Scheie, A. and Skauge, A.: "Capillary Number Relations for Some North Sea Reservoir Sandstones," presented at the 1990 SPE/DOE Seventh Symposium on Enhanced Oil Recovery, Tulsa, OK, April.

[9] Gauglitz, P.A., Laurent, C.M. St. and Radke, J.C.: "Experimental Determination of Gas Bubble Breakup in a Constricted Cylindrical Capillary," *Ind. Eng. Chem. Res.* (April 1988) No. 17340, 27–31.

[10] Hagedorn, K.: *Component Partitioning in CO_2/Crude Oil Mixtures*, PhD dissertation, Stanford University (1992).

[11] King, M.J., Falzone, A.J., Cook, W.R., Jennings, J.W., Jr. and Mills, W.H.: "Simultaneous Determination of Residual Oil Saturation and Capillary Pressure Curves Utilizing Ultracentrifuge," presented at the 1990 SPE Annual Technical Conference and Exhibition, New Orleans.

[12] Lake, W.L.: *Enhanced Oil Recovery*, first edition, Prentice Hall, Engelwood Cliffs, NJ 07632 (1989).

[13] Larson, G.L., Davis, H.T. and Scriven, L.E.: "Displacements of Residual Nonwetting Fluid from Porous Media," *Chem. Eng. Sci.* (1981) **36**, 75–81.

[14] Mohanty, K.K., Davis, H.T. and Scriven, L.E.: "Physics of Oil Entrapment in Water-Wet Rock," *SPE Reservoir Engineering* (February 1987) 113–128.

[15] Morrow, N.R. and Songkran, B.: "Effects of Viscous and Buoyancy Forces on Nonwetting Phase Trapping in Porous Media," *Surface Phenomena in Enhanced Oil Recovery*, D. Shah (ed.), Plenum Press, New York City, NY (1982) 387–411.

[16] Ransohoff, T.C., Gauglitz, P.A. and Radke, C.J.: "Snap-off of Gas Bubbles in Smoothly Constructed Noncircular Capillaries," *AIChE J.* (1987) **33**, No. 5, 753–765.

[17] Roof, J.G.: "Snap-Off of Oil Droplets in Water-Wet Pores," *Soc. Pet. Eng. J.* (March 1970) 85–90.

[18] Stegemeier, G.L.: "Relationship of Trapped Oil Saturation to Petrophysical Properties of Porous Media," paper SPE proceedings presented at the 1971 SPE Improved Oil Recovery Symposium, Tulsa, OK, April 21–24.

[19] Taber, J.J. and Seright, R.S.: "Horiozontal Injection and Production Wells for EOR or Waterflooding," presented at the 1992 SPE/DOE Eighth Symposium on Enhanced Oil Recovery, Tulsa, OK, April 21-24.

[20] Thiele, M.R., Blunt, M.J. and Orr, F. M., Jr.: "A New Technique for Predicting Flow in Heterogeneous Systems using Streamtubes," paper SPE 27816 presented at the 1994 Ninth Symposium on Improved Oil Recovery, Tulas, OK, April.

[21] Wilkinson, D.: "Percolation Effects in Immiscible Displacement," *Physical Review A* (1984) **30**, No. 1, 520–531.

[22] Wilkinson, D.: "Percolation Effects in Immiscible Displacement," *Physical Review A* (1986) **34**, No. 2, 1380–1385.

[23] Zhou, D. and Stenby, H.E.: "Immiscible Displacement in a Porous Medium Simulated by a Statistical Model," *North Sea Oil and Gas Reservoirs-II* (1990).

[24] Zhou, D., Fayers, F.J. and Orr, F.M., Jr.: "Scaling Multiphase Flow in Simple Heterogeneous Porous Media," paper SPE 27816 presented at the 1994 Ninth Symposium on Improved Oil Recovery, Tulas, OK, April.

DATE FILMED

7/14/94

END