WETTABILITY EFFECTS IN THREE-PHASE FLOW DUE TO GRAVITY DRAINAGE

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ABSTRACT

The downward displacement of oil by gas cap expansion or by gas injection at the crest of the reservoir is often an efficient method of oil recovery. This paper presents a study of the effects of wettability on gravity dominated three-phase flow at both low and high water saturations. A series of experiments of three-phase flow due to gravity drainage in bead-pack models have been performed and analysed. These experiments have been analysed using dimensionless numbers (Bond and Capillary numbers), re-defined to include the 3-phase effects of gas, oil and water. The Capillary number alone has proved insufficient to correlate oil recoveries by gravity drainage for these cases. Therefore it is necessary to include the influence of gravity. We find that the oil recovery shows a good correlation with a new dimensionless number that includes both the scaled Capillary and Bond numbers. We find that due to a different balance of the forces and the fluid morphology, we have different oil recovery rates in gravity drainage by gas displacement depending on the wettability and the balance between gravity, viscous and capillary forces.

INTRODUCTION

Gas injection is an attractive method to improve oil recovery that can be applied at connate water saturation (secondary injection), to remobilize residual oil after waterflooding (tertiary injection) or after other recovery processes (*Dawe 1991)*. When the vertical permeability of the reservoir is high the effect of gravity becomes particularly important. In the presence of three-phases, gravity leads to the segregation of the fluids according to density; this process is also affected by fluid viscosity, interfacial tensions, wettability and pore geometry. For instance, when the oil is spreading between the gas and water and the medium is water-wet, gravity forces will favour the downward film drainage of oil and so creating a zone of higher oil saturation. However, when gas is injected at residual oil after a waterflood the formation of the 'high oil saturation zone' may not always occur. It is essential to understand the dynamics of gravity segregation in order to interpret laboratory experiments and be able to predict the recovery from these processes through numerical simulators.

Wettability and spreading in 'three-phase flow' has been studied by several authors (*Vizika et al. 1994, Blunt et al. 1995, Naylor et al.1996, Dawe et al.1997, Di Carlo et al.1998*), however, the interplay of gravity and other prevailing forces has not been completely analysed for the fluid morphologies and the flow characteristics. Grattoni et al. 1997 and others (*Oren and Pinczewski 1995*) have shown that the 3-phase flow is particularly governed by the pore-scale effects, and that the displacement mechanisms are controlled by the fluid morphology as well as by viscosity, wettability, spreading coefficients and pore geometry. For instance, when the oil is spreading between the gas and water and the medium is water-wet (water covers the solid), gravity forces will favour the downward film drainage of oil and so create a bottom zone of high oil saturation. On the other hand for oil-wet conditions the oil forms a wetting film on the solid so that the water can block the gas advance. Thus, under gravity influence the fluid configuration can create conditions that result in different recovery factors due to changes in the balance of forces (i.e. gravity, viscous and capillary forces) in the different situations.

This paper reports experimental studies of the effect of gravity on two and three-phase flow conditions under different wettabilities and initial water saturations. Previously, we have identified the flow conditions for the fluid morphologies occurring for strongly water and oil-wet conditions (*Grattoni et al. 1997*). We have now extended that study to the core-scale by performing gravity drainage experiments in bead-pack models. These new experiments have been assessed through dimensionless numbers derived from 2-phase flow, Capillary number (*Chatzis and Morrow 1984*) and Bond number (*Hove et al. 1995*), and extended to 3-phase, and which allow an adequate interpretation of the 3-phase system with spreading oil. The density difference and capillary pressure have been defined differently but are still based on the fluid morphology and displacement mechanisms observed at the pore scale for relevant reservoir situations. These numbers can be used to categorise the gravity drainage process. The Capillary number showed a different behaviour according to fluid morphologies and saturation history. However, the Capillary number alone has proved insufficient to correlate oil recoveries by gravity drainage, as the gravity forces need to be included. We show that there is a good correlation between the dynamics of oil recovery and a new dimensionless number that includes both the Capillary and Bond numbers. Moreover, the recovery kinetics and the mechanisms governing the production in water- and oil-wet media have been identified through careful study of the pore scale movements.

EXPERIMENTAL APPROACH

The experiments were performed using rectangular packs of 20 by 10 by 0.6 cm packed with glass beads 0.49 to 0.70 mm in diameter. The average pore volume was 51 cm^3 i.e. porosity of 42%. These packs provide a simplistic representation of the main flow characteristics of reservoir porous rocks, but have the additional merit of being transparent, so that the movement of the fluids can be observed. The whole of the apparatus was mounted vertically, at ambient pressure and temperature. The outlet of the test section was connected to a separator where the production rates of oil and water could be measured. Figure 1 shows the experimental set-up. The fluids used were distilled water, paraffin and air. This three-phase system has a positive spreading coefficient. Table 1 gives the fluid properties.

The glass beads are water-wet, but the wettability can be changed to oil-wet by treating them with "Repelcote" (dimethyldichloro-silane in 1,1,1 trichloroetane). The wettability was maintained by first contacting the beads with the wetting fluid. At the start of an experiment, the beadpack was first filled with CO_2 and flooded with degassed water/oil (depending on the wettability) until it was fully saturated. It was then flooded with oil/water to residual saturation of the wetting phase and re-flooded to produce a residual saturation of the non-wetting phase. Spontaneous gas invasion experiments were performed by allowing the gas to enter at the top of the test section while the accumulated volumes of each of the effluent fluids were measured.

EXPERIMENTAL RESULTS

A series of experiments were performed to study the effect of wettability (water and oil-wet) and initial water saturation (connate water and after waterflood) on the three-phase flow under gravity drainage. The results will be discussed under primary recovery (connate water saturation) and waterflooded conditions (residual oil saturation). The accumulated produced fluid volumes as a function of time is shown in Figures 2-4. Smooth curves were fitted to the production data, shown as continuous lines, which were then used to calculate gas velocities.

The spontaneous gas invasion at the top of the bead-pack model involves the creation of a gas front, which advances with a variable velocity as production takes place (i.e. front advances at different velocities with time). During primary recovery only oil was recovered. Under water-wet conditions no significant movement of water was observed. In the oil-wet case however the gas front creates the formation of a zone of higher water saturation at the bottom of the test section, so showing a change in residual water saturation. After waterflooding (residual oil) only water was produced during the initial stages. A higher oil saturation region was formed below the gas front produced by the reconnection and mobilisation of oil in the water-wet condition but a change in residual oil saturation in the oil-wet case. Thus, all the saturations were changing along the model as fluid production occurred.

Under spontaneous gas invasion the velocity and shape of the gas front is controlled by the interplay of gravity, capillary and viscous forces. The balance between the viscous and capillary forces during gravity dominated flow can be considered through the Capillary Number, $N_{Ca,}$ (*Chatzis and Morrow 1984*). As the front velocity, v_g, varies with production the Capillary number will be a dynamic parameter. The Bond number, N_B, (*Hove et al. 1995*) takes into account the balance between gravity and capillary forces and is directly proportional to the advance of the gas front. N_B is a dynamic parameter depending also on the fluid distribution and the wettability.

The velocity of the gas front, which is proportional to the oil mobility, for the water-wet condition under primary drainage is shown in Figure 5. In this graph the different stages of the displacement and the balance between mechanisms can be followed. During the first stage the gas invades the larger pores controlled by the capillary and viscous forces in the oil but as the production continues the gravity forces becomes more pronounced and the gas moves preferentially in the horizontal direction. The square marker shows the point where the gravity forces are of the same order as the capillary forces (i.e. N_B =1, this point is discussed later). When the gas reaches the lower part (oil recovery ~0.63) there is a transition from bulk oil displacement to oil film drainage, which is a slower process and depends on the film thickness. This explains the changes in slopes at different regions of the production curves versus time.

PORE LEVEL MORPHOLOGY AND DIMENSIONLESS NUMBERS

An physical insight into some of the factors that determines the movement of the phases and its influence on the dynamics of the recovery can be obtained by studying the fluid configuration and the controlling factors at the pore level. For this purpose, we have extended the traditional Bond number and Capillary dimensionless numbers for 3-phase flow under different wetting conditions. These two dimensionless numbers include the relative magnitude of the viscous forces, buoyancy forces and capillary forces within the pore structure that controls the movement of the interfaces. The following description is for a spreading oil under strongly wetting matrix but it can be applied to non-spreading oil and other wetting conditions (*Grattoni et al. 1997, Pingo Almada 1997*).

The Capillary Number (N_{Ca}) is a dimensionless group that measures the relative strength of the viscous to the capillary forces. For two- phases it can be defined as:

$$N_{Ca} = \frac{Q\,\mu}{\phi\, A\, L\, P_c} \qquad [1]$$

where Q is the flow rate of the displacing phase, μ is the viscosity of the displacing phase, ϕ is the porosity of the pack, A is the transverse area of the pack, L is the length of the pack and Pc is the capillary pressure. Displacements for the 3-phase systems under study are controlled by different interfacial tensions depending on their configuration as will be described later for each case.

The Bond Number (N_B) is also a dimensionless group that measures the relative strength of gravity (or buoyancy is some cases) and capillary forces. For a single ganglia of non-wetting phase it can be expressed as:

$$N_B = \frac{\Delta\rho g r h}{2\sigma} \qquad [2]$$

where Δρ is the density difference between the two fluids, g is the gravitational constant, r is the radius of the pore throat through which the interface must pass, h is the height of the ganglion and σ is the interfacial tension.

Figure 6 represents a leading interface of continuous gas displacing oil. If the gas and oil pressure at the top are P_g and P_o respectively, the corresponding pressures at each side of the interface located a distance z from the top are ($P_g+\rho_g$ gz) and ($P_g+\rho_o$ gz). The criterion that the interface will pass through a pore throat of size r is given by:

$$(P_g - P_o) - \Delta\rho\, g\, z > \frac{2\sigma_{go}}{r} = Pc_{go} \qquad [3]$$

More generally, during the gas movement the interfaces will pass through pore throats of different radii and the gas invasion at different positions will be controlled by the pore throat topology. So if the gravity influence is small the gas filament will grow following the spatial distribution of pore sizes (*Hawes et al. 1997*). At some stage the gas filament will have grown to the extent that the gravity forces will influence further growth and the growth will be favoured mainly at the top of the filament. There will be a smooth transition between a capillary dominated (N_B<1) and gravity dominated (N_B>1) displacement. The average pore throat radius, Ra, and average position of the gas interface, L, can be used for defining the Bond number as:

$$NB = \Delta\rho\, g\, L \,/\, Pc_{go} \qquad \text{where} \qquad Pc_{go} = 2\sigma_{go} \,/\, Ra \qquad [4]$$

When three phases are present the displacement is controlled by different interfacial tensions depending on their configuration. Also three densities are involved. These conditions complicate the definition of a unique Bond number, and really different density differences and capillary pressures are needed depending on the wettability of the matrix. A new definition seems therefore appropriate. It will be defined later for each case depending on the controlling interfacial tension (capillary pressure) and density difference for each case according to the fluid configuration.

Water-wet condition

The fluid configuration for a spreading oil under water-wet conditions is shown in Figure 7a. Water forms a stable wetting film along the pore walls while the oil forms a spreading film, of variable thickness depending on the pore structure, between the water and gas.

When gas is injected at connate water saturation the water is immobile and the gas displaces oil from the larger pore throats only. At later stage the smaller pores will be invaded by gas. The oil will drain down through oil films controlled by the density difference and the oil viscosity. Thus, the displacement is controlled by the gas-oil density difference ($\Delta\rho_{go}$) and the gas-oil interfacial tension (σ_{go}).

After waterflooding and before being contacted by gas the oil is trapped as isolated ganglia, as shown in Figure 7 a. When gas is injected the oil forms a film between the water and gas and as the gas advances more oil is contacted and reconnected. In this case the displacement is controlled by the oil-water interfacial tension (σ_{ow}) because the gas-oil interface is always preceded by the oil-water interface. At high gas velocities and due to the high gas mobility, some oil will be left behind but will slowly drain due to gravity. Thus, the initial density difference controlling the movement is gas-water but at a later stage the gas-oil density difference will take over control. However, at low gas velocities an oil bank can be formed ahead of the gas front but later will drain through films, so the gas-oil density will always control the gravity forces i.e. a significant mechanistic difference.

Oil-wet condition

The fluid configuration for a spreading oil under oil-wet conditions is shown in Figure 7b. Oil now forms the stable wetting film, of variable thickness depending on the pore structure, along the pore walls. The water and gas are the non-wetting phases and are separated by an oil spreading film.

When gas is injected either the oil-gas or oil-water interfaces can control the movement depending on the values of the interfacial tensions and the size of the pore throats at which each interface is located, so that the movement will occur at the throat of lower Pc. For instance in Figure 7b unless the pore throat 2 is one and a half times larger than pore 1 the oil-gas interface will advance through 1, because it has the lower interfacial tension. As in our case, where both interfacial tensions are similar (Table 1), the path will depend strongly on the pore throat size distribution within the media. Thus in our calculations we will use the gas-oil interfacial tension for calculating the capillary pressure. However, for other systems where there is a larger difference between interfacial tensions or a wider pore size distribution, this approximation may not be appropriate.

The density difference used for the Bond number is more complex because gas and water can both move under gravity, and the lower oil-water density difference can control the overall driving forces. At the pore level, water ganglia can be located at the bottom or in-between a gas filament thereby changing the magnitude of the force. At the larger scale the saturations of the two non-wetting phases brings a significant factor to the density contrast. Thus, we define the density difference for the oil-wet condition when 3-phases are present as:

$$\Delta\rho = (\Delta\rho_{g-o}\, S_g) + (\Delta\rho_{o-w}\, S_w) \qquad [5]$$

where $\Delta\rho_{g-o}$ is the gas-water density difference, $\Delta\rho_{o-w}$ is the oil-water density difference; S_g and S_w are the gas and water saturations. As the saturations of the three phases will be changing during flow the Bond number will change during a displacement. Thus, N_B will depend on these saturations as well as the average distance advanced by the gas.

ANALYSIS OF RESULTS

The Bond and Capillary numbers were used to interpret the total production of oil and water for three-phase flow. In performing this analysis the wettability of the media and the controlling factors for the displacement are taken into account.

Primary recovery

Water-wet condition: When primary recovery is carried out, oil is at high saturation and water at connate saturation. Gas injection at the crest of the model determines the flow through films as well as the bulk because of the high oil saturation. The continuity of oil is maintained along the porous media because of the spreading condition of the oil. Water is not mobilised but wets the pore walls and is continuous.

During the process of gravity drainage the gas front moves with variable velocity which follows the Capillary number (Figure 8). The process starts with a gas front velocity that goes in decline until the end of the process because the thickness of the oil films decreases as production takes place. However the recovery is also a function of the gravity forces; therefore we observe that the Bond number (N_B) increases linearly from zero to 2.24, indicating that by the end of the gasflooding the gravity forces have increased twofold compared with the interfacial forces. The point where the value N_B equals to 1, (gravity forces equals the capillary forces) is shown in the Capillary number curve by a square.

Oil-wet condition: During the flow of a spreading oil in an oil-wet medium, the oil production is governed especially by the fluid morphology. After gas has invaded the region, oil flows through wetting films, gas as mainly continuous non-wetting filaments and water in the form of isolated ganglia. Thus for oil recovery the oil viscosity and the pore structure are the main controlling factors. The existing connate water plays a blocking role during the displacement so creating a slower and variable oil production rate compared to the water-wet case. This is reflected in the Capillary number (Figure 8). Additionally, there is a smooth transition between capillary dominated flow to film drainage when the production is ~ 0.4 pore volumes, due to the saturations and continuity of the gas phase. The Bond number, now involving the saturation terms, for our example is shown in Figure 9. The influence of gravity forces becomes apparent when the Bond number rises to approximately 0.15. Clearly the Bond number behaviour is non-linear and does not rise above 1.0. Thus compared to the water-wet condition, the gravity forces, although important, are less significant than the capillary forces and clearly from our observations the gas displacement front is more fingered.

Waterflooded conditions

When gas injection and gravity drainage occurs in a waterflooded reservoir the oil saturation is usually lower (<50 %). This is because the oil is mainly immobile and the wettability determines its distribution and its physical form i.e., isolated ganglia or residual wetting films. For the analysis of this scenario the total production (water and oil) has been used for calculating the position of the gas front and its velocity.

Water-wet condition: Under these conditions the non-wetting residual oil is in the form of ganglia and must be reconnected before it can flow. If the gas velocity is low an oil bank can be formed. The oil spreading films formed between the gas and water are thin and not very mobile.

Similar to gravity drainage-primary recovery the gas front advances with a variable velocity and similar shape. Figure 10 shows that the Capillary number can indicate the different mechanisms involved (capillary dominated, gravity and film drainage). The Bond number increases linearly from zero to 1.61. The distinctive point to note is that the oil production increases significantly after the Bond number is closer to 1, showing that the main production mechanism is oil film drainage.

Oil-wet condition: After waterflooding in an oil-wet medium, the residual oil is in the form of wetting films and fills the smaller pore throats and its continuity is assured along the pore walls. The displacement is capillary dominated with a transition to film drainage (Figure 10). The Bond number is larger than in primary drainage but it only reaches 1.1, Figure 11. The oil becomes mobile only after the gas has invaded the region, so the main mechanism is wetting film drainage. The oil production starts very soon due to the continuous nature of the oil but significantly increases when the Bond number <0.6. The final oil recovery is similar to that for the water- wet case.

New Dimensionless Number

In order to combine the varying strengths of all the forces acting at different stages during a displacement, a combination between the Capillary and Bond number is necessary. The viscosity ratio between displaced phase (μ_d) and displacing phase (μ_g) should be included in order to account the fact that the oil viscosity is approximately 50% higher than the water viscosity and very much larger than gas. We propose a combined number, N, of the form:

$$N = a\, N_B - b\, (\mu_d/\mu_g)\, N_{Ca} \qquad [6]$$

Where a and b are scaling constants, N_B is the Bond number and N_{Ca} is the Capillary number. This combined number shows a good correlation with the total recovery for all the situations studied when the constants are a= 0.346 and b= 5960. The results are shown in Figures 12- 13. The slope is close to unity for the water-wet media and after waterflooding in the oil-wet media. Primary recovery for the oil-wet case correlates well with the new number although it has a larger slope. The reason for this larger slope may be due to the blocking effect of the residual water, which is located in larger pores reducing the velocity of the gas (i.e., lower values of N_{Ca} and N_B).

The oil production as a function of the scaled number for the waterflooded conditions is shown in Figure 14. Both oil-wet and water-wet conditions have a similar behaviour showing that two different mechanisms are in action. In the oil-wet case film drainage occurs as oil is remobilized near the top of the model (lower residual saturation to gas) and it is continuous as a wetting film so oil drains down, but the process is slow as the density difference with the water is small. At the second stage oil also drains along films but the density difference with the gas is larger so making the oil movement faster. For the water-wet case during the first stage the oil is collected below the gas front by reconnection, and is produced later as an oil bank. The second stage corresponds to film drainage between the water and the gas.

CONCLUSIONS AND DISCUSSION

We have performed a series of three-phase experiments under gravity conditions to study the influence of the ratio of the gravity, viscous and capillary forces acting and the mechanisms involved during the displacement. Experiments were performed on water-wet and oil-wet beadpacks at connate water and waterflooded conditions.

The examination of the recovery rates by gravity drainage has showed that different behaviour of the gas, water and oil displacement depends on the different fluid morphologies and the balance between capillary, viscous and gravity forces. For primary recovery at early stages the oil is produced as a bulk and is controlled by the capillary and gravity forces, but later film drainage occurs and is controlled by the gravity and viscous forces. In the oil-wet case the residual water blocks and restricts the gas flow. For waterflooded conditions the oil is mainly produced by two processes: for water-wet conditions, an oil bank formation and film drainage and for oil-wet conditions by wetting film drainage.

The forces acting during 3-phase flow can be incorporated through an extension of Capillary and Bond numbers, but Capillary number alone does not correlate well with oil recovery because gravity forces are not included. A new dimensionless number has been defined which includes the 3-phase effects of gas, oil and water and the morphology at pore scale (fluid arrangement and interaction) and the overall behaviour at core scale. This new number shows the influence of viscous, capillary and gravitational forces and the mechanisms involved and it has a good correlation with the total recovery. The understanding of the mechanisms involved at pore scale and then including the prevailing physics into dimensionless numbers could improve the up-scaling lab results into the reservoir.

AKNOWLEDGENTS

The authors wish to thank the EPSRC for providing financial support to this project.

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Table 1. Properties of the fluids used.

	ρ (Kg/m^3)	μ (mPa.s)
Paraffin (oil)	**764**	**1.56**
Water	**1002**	**1.00**

σ_{ow} (mN/m)	σ_{og} (mN/m)	σ_{gw} (mN/m)
34.1	**24.0**	**71.1**

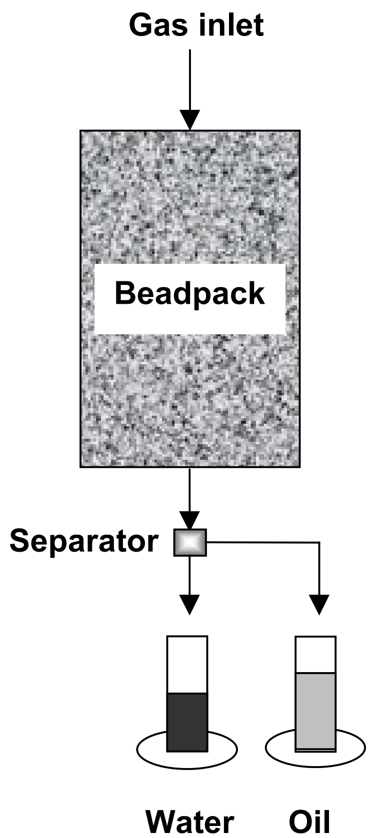

Figure 1- Experimental set-up.

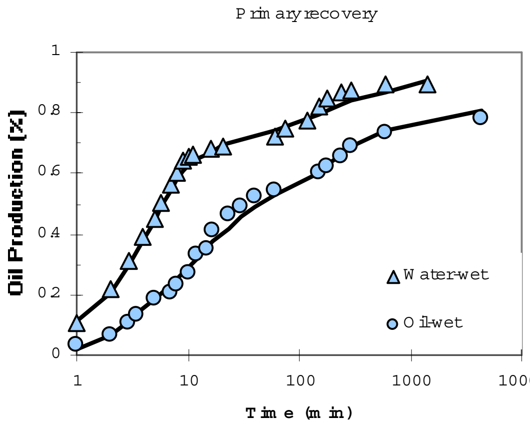

Figure 2- Oil production during primary recovery.

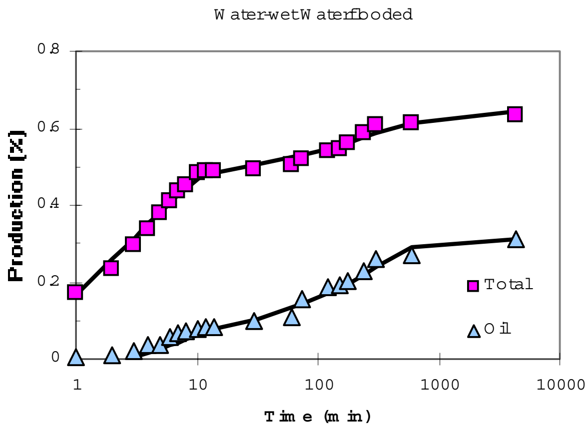

Figure 3- Production after waterflooding. Water-wet.

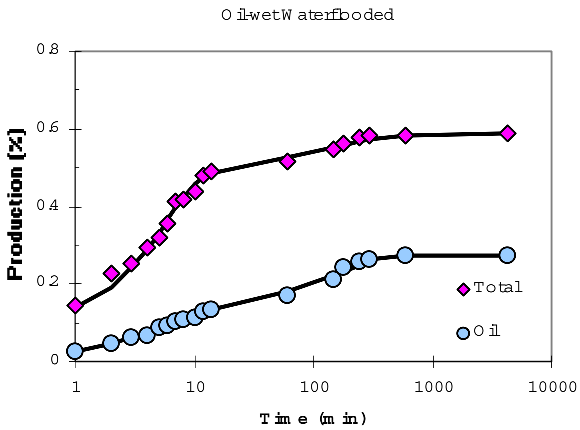

Figure 4- Production after waterflooding. Oil-wet.

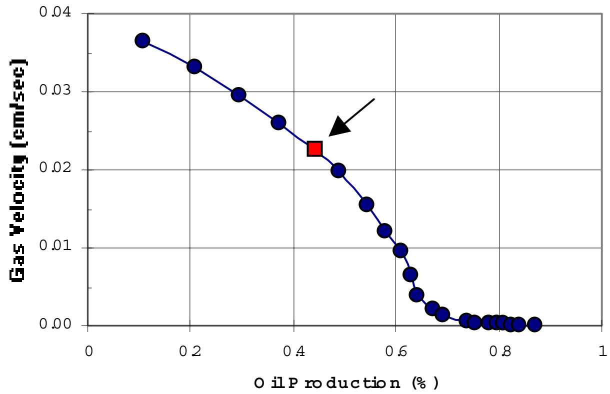

Figure 5- Gas velocity during primary recovery. Water-wet.

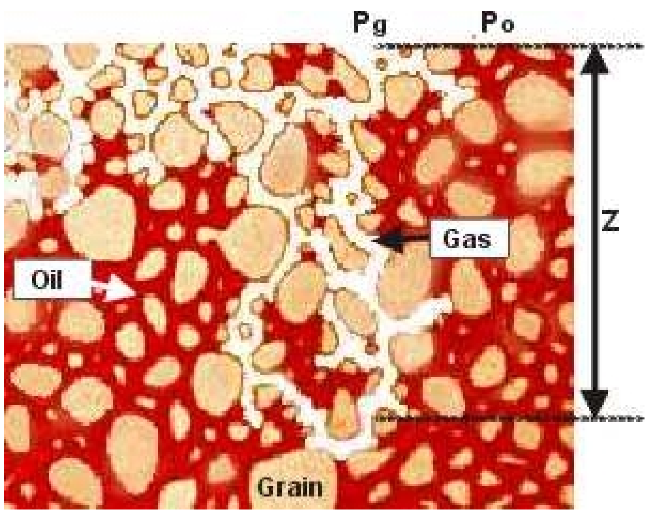

Figure 6- Gas displacing oil under gravity influence.

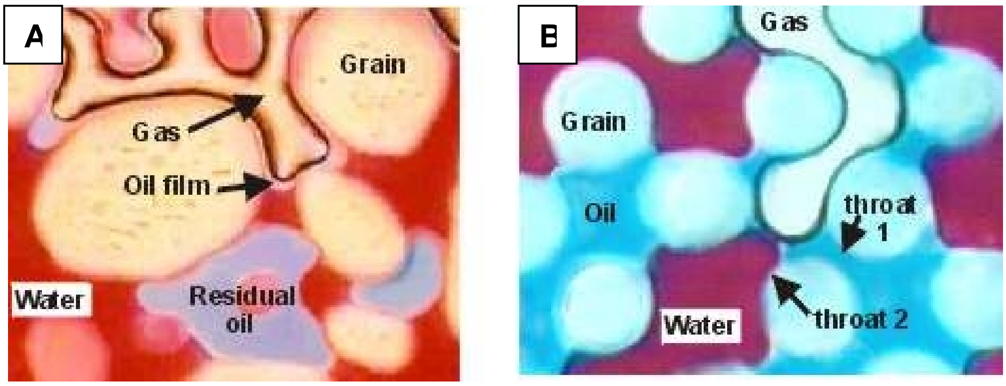

Figure 7- Fluid configurations for a spreading oil. **A**. Water-wet **B**. Oil-wet

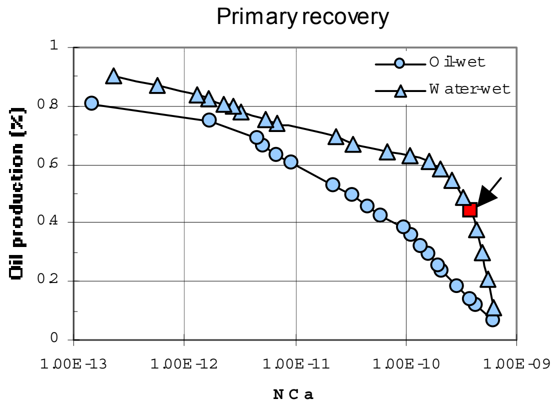

Figure 8- Capillary number during primary production.

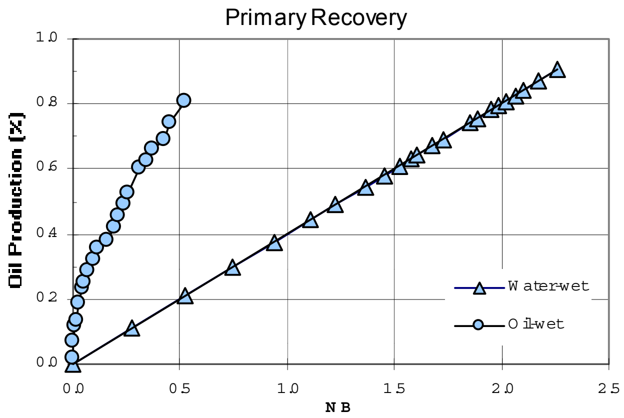

Figure 9- Bond number during primary production.

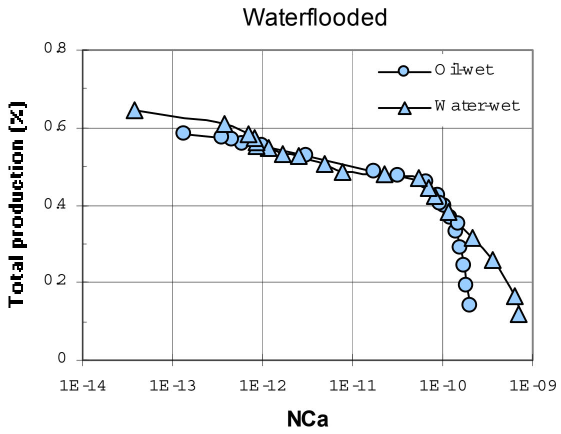

Figure 10- Capillary number vs. total production. Waterflooded condition.

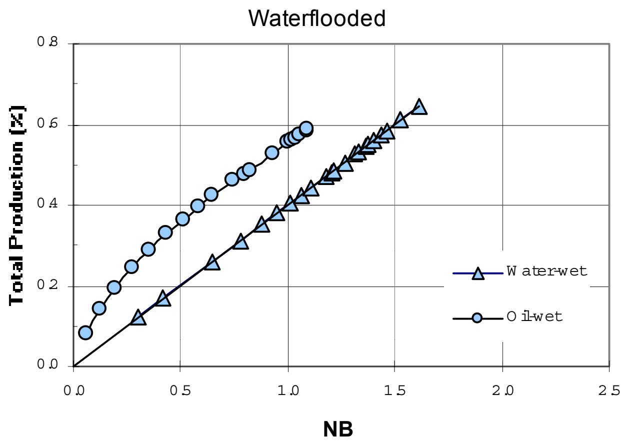

Figure 11- Bond number vs. total production. Waterflooded condition.

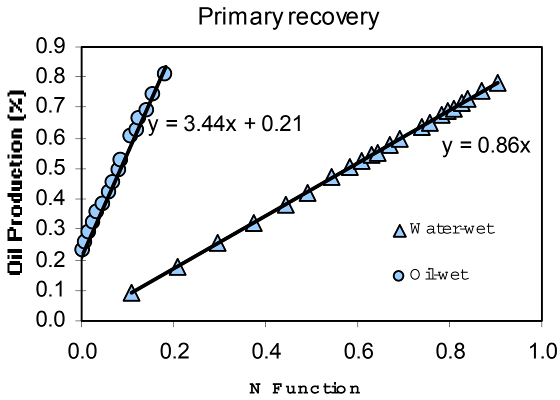

Figure 12- New dimensionless number vs. oil production. Primary recovery.

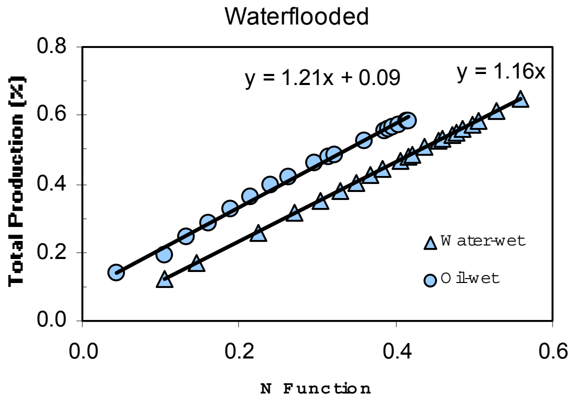

Figure 13- New dimensionless number vs. total production. Waterflooded conditions.

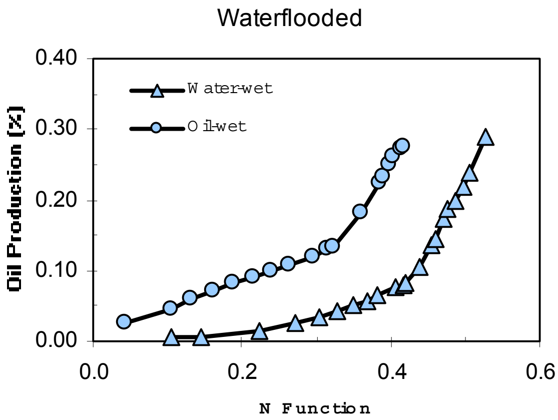

Figure 14- New dimensionless number vs. oil production. Waterflooded condition.