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Facies-Seabed Capillary Pressure Analysis for Offshore Nigerian Reservoirs

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ABSTRACT

A large number of primary drainage capillary pressure measurements have been conducted for various geologic facies found in Nigerian oil reservoirs, in the Mobil Producing Nigeria Joint Venture acreage. Various methods such as porous-plate, centrifuge, and mercury injection were used to measure capillary pressure under reservoir net confining stress. Furthermore, attempts were made to scale the capillary pressure data using after they were associated with geologic facies. A general correlation was also developed to relate irreducible water saturation to petro physical properties so that the data can be used in situations where geologic facies is not identified. In this paper, we will: classify more than 400 primary-drainage capillary pressure data sets, from various measurement methods, according to geologic facies; compare porous-plate and centrifuge primary drainage capillary pressure data to demonstrate good agreement between the results from these techniques. Show the utility of mercury injection data for high quality facies, as well as the optimistic nature of the data for lower quality facies; show representative primary drainage capillary pressure curves, and their associated uncertainty, for geologic facies found in the offshore Nigeria acreage; demonstrate the utility of conventional scaling methods including J-function, show the correlation of irreducible water saturation with petrophysical properties for Biafra, intra Qua Ibeo (IQI) and lower Biafra sands, provide guidelines for screening cores, sampling and primary drainage capillary pressure' measurements were proposed. Results of this study may be used to calculate gas and oil in-place and to model capillary pressure for scoping studies of undeveloped reservoirs in the J.V. area. The characteristic capillary pressure data can be the best source of data for resistivity log calibration and calculation of irreducible water saturation in area where core data are not available. The methodology can be used for measuring and modeling capillary pressure in a more efficient and reliable way in sediments of similar environment of deposition.

Keywords: Goelogic facies, capillary, reservoir, pressure, injection, irreducible water, saturation and porosity.

INTRODUCTION

In the Nigerian offshore J.V. acreage, three types of reservoir sands are recognized: Biafra, found at 4000-8000' depth, massive shallow marine sand deposits; Intra Qua Iboe (IQI), 9000-10000' deep marine turbidite deposits; and Deep Biafra, 10500-12000'; coarse grain channel sands. The distribution of these stratigraphic units in the offshore JV acreage is shown in Figure 1. The productive reservoir sands are mostly unconsolidated/friable quartzose sands, with little clay. Diagensis plays a relatively small role in determining reservoir quality. In our geologic model, each reservoir rock type is sub-classified into facies, based on depositional environment, lithology, and logsignature. Each facies is then quantified in term of petrology, routine, and special core analysis. The facies effectively subdivide the body or reservoir rocks into groups that display meaningful trends in the petrophysical properties of porosity, permeability, capillary pressure, relative permeability, and formation compressibility. Reservoir facies provide the critical relationship among reservoir lithoiogy, petrophysical properties, and wire-line signature. These quantitative geologic models and reservoir facies are used in virtually every phase of reservoir evaluation and reservoir management.This work describes the variability and trends in the capillary pressure behavior and water saturation of the facies in the three types of reservoir found in the offshore Nigerian J.V acreage.

Capillary Pressure Fundamental Concepts

Capillary forces determine the strength with which a wetting phase is held in a porous medium. Capillary forces control:

- the initial distribution of fluids in a reservoir
- the residual hydrocarbon saturation after any displacement process, and
- the integrity of the seal of the reservoir.

Consequently, high quality data are needed to accurately assess the hydrocarbon in-place and reserves.

Drainage refers to a process of reduction in the wetting phase saturation which is often water. Imbibition refers to a process of increasing wetting phase saturation. Primary drainage capillary pressure tests simulate the original charging of a reservoir with a non-wetting phase, gas or oil.

Primary drainage capillary pressure curves are used to estimate the reservoir connate water saturation above the original water-oil contact. Both the thickness of the transition zone and the irreducible water saturation can be determined from these data. The threshold pressure obtained from the primary drainage capillary pressure curve is used to determine the offset between the water-oil contact and the free-water level. This information is needed so that water saturations in the reservoir can be estimated from the lab- measured capillary pressure data. Drainage capillary pressure data can also be used to estimate the pore throat/pore body size distribution of the sample. All of the capillary pressure data discussed in this paper are primary drainage type.

Two other types of capillary pressure data are important to the oil industry. Gas-oil drainage capillary pressure is measured on samples containing an initial water saturation to estimate the residual oil saturation for processes involving immiscible gas displacing oil. Imbibition capillary pressure data is used to calculate the minimum residual oil saturation for water-oil displacement processes. It is also an indicator of the wettability of the sample.

In a primary drainage capillary pressure measurement, normally the sample is initially saturated fully with a wetting phase, typically brine. The non-wetting phase, other gas or oil, is forced into the rock, displacing the wetting phase, using a sequence of increasing pressure steps. At each applied pressure step, the saturation is allowed to equilibrate and the amount of fluid displaced (or injected) is measured. In the case of mercury injection, the sample is evacuated, and the non-wetting phase, mercury, is forced into the rock, displacing the wetting phase, mercury vapor, using a sequence of increasing pressure steps.

The fundamental equation that relates capillary pressure to the pore throat size of a porous medium and the fluids in the pores is: $P_c = (2/r)\ .\text{ϭ}\ .\ \cos(\Theta)$

(Eqn. I)

Where,

P_c = capillary pressure, dynes/cm^2

r = the pore throat radius, cm

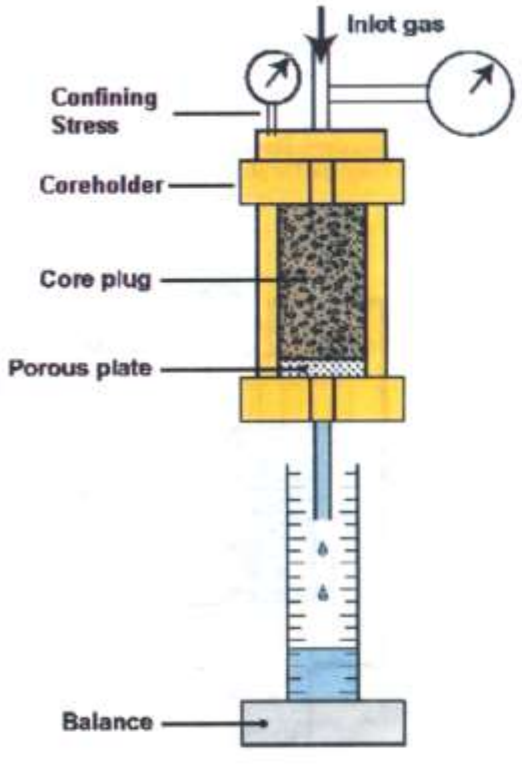
ϭ = interfacial tension between the fluid phases dynes/cm

Θ = contact angle between the solid surface and the fluid-fluid or gas-fluid interface, degrees.

The inverse relationship between pore throat size and capillary pressure is shown in the above equation. The equation also shows the absence of capillary pressure when the interfacial tension between fluid phases approaches zero. The classification of capillary pressure data based on geological facies is related to the variation of pore throat/pore body size distribution associated with each facies. It is also important to mention that capillary pressure data are measured with immiscible fluids to reflect the immiscible processes that take place in exploitation of the reservoir.

Methods of Capillary Pressure Measurements

There are three methods that are commonly used to measure capillary pressure in a rock, (I) the porous plate method, (2) the centrifuge method, and (3) the mercury injection technique. Each method has its advantages and disadvantages.



Porous Plate

The porous plate technique employs a strongly water-wet, typically, porcelain plate having very fine pores of uniform size. When saturated with a wetting phase the plate exhibits a high threshold pressure to the entrance of a non-wetting phase. The porous plate is used to isolate a chamber containing a core sample, also saturated with the wetting phase and in capillary contact with the plate. If the core sample is exposed to the non-wetting phase and

a differential pressure is applied between that phase and the external side of the plate, the non-wetting phase is forced into the core, wetting phase is displaced into and through the porous plate.

In a test, the non-wetting phase pressure is slowly increased until the threshold pressure of the core sample is reached. The pressure is then reached stepwise, and each pressure level is maintained until production from the sample ceases.

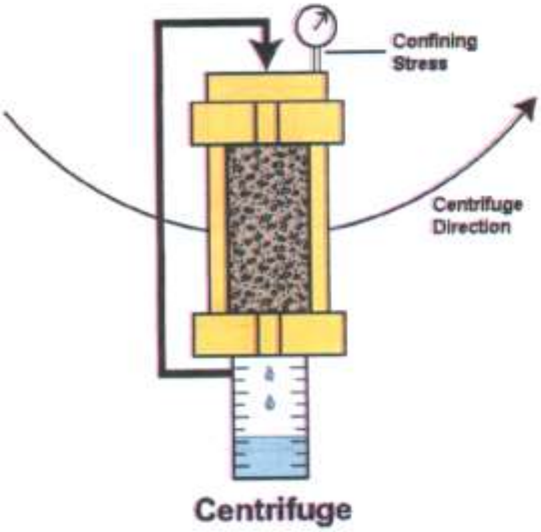
In general, the porous plate method is considered to be the most accurate of the three methods. It can be used on heterogeneous or laminated samples and since the saturation distribution of the fluids at the end of the experiment are considered uniform throughout the sample, no interpretation model is needed (as when using the centrifuge method).

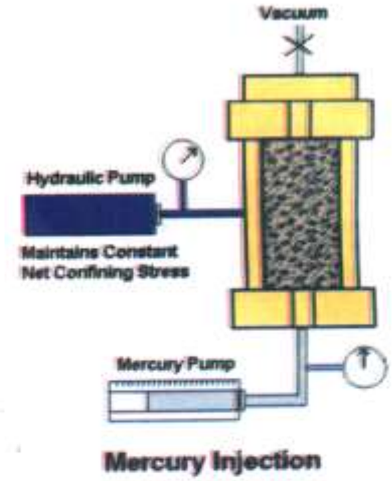
However, a porous plate experiment is much slower than the other methods. Typically, nearly a month may be required to reach equilibrium at each step.

In the centrifuge technique, individual core plugs containing a high saturation of a single phase are mounted in core holders and placed in a centrifuge. The plugs are in contact with a second fluid phase. Centrifugal force applied by rotating of the sample generates a pressure gradient in each fluid phase that differs according to the fluids density. As the first phase is produced from one end of the core plug the second phase enters from the opposite end to replace it. The centrifuge speed is then increased stepwise and is maintained constant at each step until production ceases The cumulative production of the produced phase is measured at each speed. Depending on the configuration of the core holder, either the less dense or the more dense phase can be produced.

The centrifuge method is much faster than the porous plate, but not as fast as the mercury injection method. A typical equilibration time for each step is about one week.

However, the centrifuge method is not recommended for heterogeneous or laminated rocks because the data analysis method may not accurately account for the distribution of fluids in a heterogeneous rock. Also, for highly permeable rocks, very limited data may be reliably collected at low capillary pressures.





In the mercury injection technique, a sample that has been extracted, dried, and evacuated is immersed in liquid mercury. Pressure is then increased stepwise, and the amount of mercury entering the sample is measured and converted to non-wetting phase saturation. Since mercury is strongly non-wetting in core material, these are drainage measurements.

Since the pressure of the gas phase (mercury vapor) is very small the absolute pressure of the liquid mercury is the capillary pressure, and mercury saturation can be calculated directly from the mercury uptake and the sample pore volume.

The mercury injection method is the fastest of the three methods. A measurement usually requires less than one day. And very high capillary pressure (2,000-70,000psi) psi) can be achieved to characterize the smallest pores. The method can be applied to small and irregularly shaped rocks (e.g. drill cuttings).

However, since mercury is not a reservoir fluid, the method does not usually replicate reservoir displacement processes accurately, Mercury injection data should he validated using one of the other two methods before it is used for calculation of fluid distribution in the reservoir.

Sampling and Sample Handling

Capillary pressure measurements should always be conducted under confining stress to accurately duplicate the pore structure under reservoir net stress, Samples should be selected to cover the range of porosity and permeability within a facies. These mostly unconsolidated samples must be handled carefully to assure that their mechanical integrity is undisturbed. Stress cycling should be avoided, because it can change the pore structure. Measurements should be made to high enough capillary pressure to cover the height of the reservoir it represents.

Core plugs should be carefully cleaned to assure a strongly water-wet sample. Lower quality samples, with permeability less than 100 mD or $(k/\Phi)^{0.5} < 2$, should be examined carefully to assure that conventional cleaning and drying do not alter the pore fabric of the rock.

Analysis of Capillary Pressure Data, Offshore Nigerian Fields

This paper discusses the analysis of 477 capillary pressure tests (426 porous plate or centrifuge and 51 mercury injection) on fifteen offshore Nigerian fields in the J.V. acreage, comprising twenty reservoirs. The fields evaluated were:

Biafra: Asabo, Ekpe, Ekpe WW, Eku, Enang, Ubit, Usari, Utue, Yoho
Intra Qua Iboe: Asasa. Edop, Etim
Deep Biafra: Oso, Usari

For each field, capillary pressure tests were run on all of the important reservoir facies.

Average laboratory air-brine primary drainage capillary pressure data for all important Biafra facies are shown in Figure 2. The data were obtained with air-brine porous plate method, measured under net confining stress.

The average for each facies is obtained using the Leverett J-function scaling technique (Ref. 1). In this technique, capillary pressure is assumed to be a function of both porosity and permeability and a functional form for this relationship is assumed. An assumption with this technique is that all of the capillary pressure curves for a given rock type can be represented by a single, dimensionless J curve. The form of the J-function is:

$J = 2.17\,[P_c/ʊ\,\cos(\Theta)].[k/\,\Phi]^{0.5}$ (Eqn. 2)

Where,

J = J value at a given saturation, dimensionless.
P_c = capillary pressure at a given saturation, psi,
ʊ = interfacial tension, dynes/cm,
Θ = contact angle, degrees,
k = permeability, mD,
Φ = porosity, %,

and 2.17 is a unit conversion factor that is appropriate with the units given above,

It is evident in Figure 2 that each geological facies has its own characteristic capillary pressure. [he irreducible water saturation varies from 6% to 55%, with lower quality facies having the higher saturations and thicker transition zones.

Similarly, the average air-brine primary drainage capillary pressure curves for all important facies for IQI reservoirs are shown in Figure 3. The main characteristics of IQI capillary pressure is that the high quality facies have very similar Pc curves, whereas the facies 3_c has very high saturations and transition zone thickness. The reason for the similarity in Pc of high quality IQI rocks is due to their better sorting as a result of their deep water turbidite deposition environment, The high quality fades have 10-15% S_{wi} whereas the lower quality facies could have S_{wi} greater than 50%.

The average Pc curves for productive Deep Biafra facies are shown in Figure 4. The Pc curve is systematically distinguished based on their facies classification, The irreducible water saturation varies from 6% for fades Ia to 27% for fades 3. The transition thickness for Deep Biafra fades is rather short because the formation is more consolidated, with some quartz cementation, and the rocks contain fewer small pores.

A correlation was developed that relates water saturation at capillary pressure of 100 psi vs the square root of air permeability / porosity, all measured under simulated reservoir Net Confining Stress, Figure 5 shows this correlation for Biafra facies, The choice of 100 psi (corresponding to a height of about 300 feet in the reservoir) is arbitrary. But, 100 psi coincides with the maximum air-brine capillary pressure that is common in most of the measurements, and is close to the point at which most of the capillary pressure curves become vertically asymptotic. In this figure, primary drainage mineral oil-brine capillary pressure converted to an air- brine equivalent is superimposed on laboratory air-brine measured data. The conversion is accomplished using the following equation:

Where,

P_c = capillary pressure, psi
ƍ = interfacial tension, 70 dynes/cm for air-brine; 27 dynes/cm for oil-brine
Θ = contact angle, 0 degrees for air-brine, 30 degrees for oil-brine
o-b = oil - brine conditions
a-b = air - brine conditions

Excellent agreement was observed between the two types of measurement, indicating that both air-brine and oil- brine tests are comparable, and air brine can be used instead of the more cumbersome oil-brine tests, unless wettability other than strongly water-wet condition during primary drainage is suspected.

A similar correlation between water saturation at 100 psi and the square root of air permeability / porosity, at net confining stress, was developed for both IQI and Deep Biafra facies, as shown in Figure 6 and 7, respectively.

The S_w @ P_c=l00 psi vs. $(k/Ø)^{0.5}$ composite plot for all Biafra, IQI, and Deep Biafra facies together is shown in Figure 8. The figure shows a similar correlation of S_w @ 100 psi vs. $(k/Ø)^{0.5}$ down to $(k/Ø)^{0.5} \geq 5$. For $(k/Ø)^{0.5} < 5$, water saturations in Biafra facies appear to be higher than those found in IQI and Deep Biafra rocks. Deep Biafra facies have the lowest water saturations in lower quality rocks.

For each facies, there is a range of porosity and permeability that is associated with that facies. Therefore, a range of capillary pressure curves are expected, representing this variation in petro physical properties. Figure 9 shows this variation from the average Pc for IQI facies 2 and 3b, as exhibited by (Inc standard deviation from the average.

An investigation was made of the effect of averaging technique for capillary pressure data. The four techniques evaluated were: J-function averaging, arithmetic saturation averaging at selected Pc, averaging the product of saturation and porosity, and averaging the product of saturation and $(kIØ)^{0.5}$. Each method was applied to all data sets. Little difference in the results was observed when an adequate number of measurements were available. However, the different averaging techniques produced significantly different average Pc when an inadequate number of measurements were available. This is shown in Figure 10, where only eight measurements on widely different petro physical properties were available for Deep Biafra facies 3a. Based on the above investigation, we do not recommend weighting saturation with (k)Ø)°' to generate average Pc curves.

In another investigation, water saturation at 100 psi obtained from air-brine centrifuge capillary pressure was superimposed on porous plate data to compare the two measurement techniques. The limited number of centrifuge data, measured under NCS, analyzed by the Hassler-Brunner technique (Ref. 2), showed good agreement with the porous plate data, Figure II. This indicates that the techniques generate comparable results if rigorous procedures are adopted.

Irreducible wetting phase saturation, at equivalent to gas- water P of 100 psi, from mercury injection capillary pressure measurements, obtained under confining stress, showed good agreement with porous plate and centrifuge data for high quality facies. However, the unrepresentative lower irreducible saturations at l psi equivalent air-brine P was obtained for lower quality facies. $(kØ)^{0.5} < 5$, as shown in Figure 12 demonstrate the unreliability of mercury injection data.

Validation

Primary drainage capillary pressure measurements are often conducted on thoroughly cleaned core. This reflects the strongly water-wet conditions that existed prior to hydrocarbon migration into the reservoir. However, there are situations where capillary pressure of strongly water-wet samples may not represent the wettability of the reservoir at lime of discovery. To confirm that the strongly water-wet condition applies to a reservoir, it is advisable to obtain cores taken with a bland oil-based mud (OBM) and directly measure the water saturation. Cores from several offshore Nigeria fields were obtained using OBM, and water saturation was measured using the Dean Stark technique. The results were compared with irreducible water saturation from gas-water capillary pressure tests, as shown in Figure 13. The good agreement indicates that the strongly water-wet condition represents the wettability of each of these reservoirs during the primary drainage process. Therefore, capillary pressure measurements on thoroughly cleaned samples are appr for representing the initial water saturation in these reservoirs.

Rest Practices, Primary Drainage Capillary Pressure on Unconsolidated Sands

Sampling and Sample Selection

1. Screen samples based on CT scanning & petrographic analysis
2. Ensure that permeability and porosity of P. samples cover the entire range of the facies.

Measurement Techniques and Conditions

1. Clean core carefully to strongly-water wet condition, without altering the pore structure or mechanical integrity of the rock.
2. Use a synthetic brine, based on field brine chemistry. to avoid alteration and movement of clays.
3. Use the centrifuge technique for homogeneous plugs if electrical property measurements are not needed.
4. Use the porous plate technique for heterogeneous plugs or if electrical property measurements are
1. Make all measurements (g-w or o-w) at simulated initial reservoir net confining stress.
2. Make complementary measurements of k, k, f, k @S at net confining stress, and live oil-water IFT.

Number of Measurements and Sample Dimensions

1. Number of measurements: 6-10 samples per facies, 24-50 samples per reservoir (twice as many measurements are needed for heterogeneous rocks).
2. Sample size 1 5” diameter by 2” long core plugs.

CONCLUSIONS AND RECOMMENDATIONS

In this paper we:

- Provided guidelines for screening cores, sampling and primary drainage capillary pressure measurements.
- Showed that facies-based classification is valid for drainage capillary pressure modeling and prediction.
- Applied facies-based capillary pressure modeling regionally to cover 20 major reservoirs in offshore Nigeria.
- Showed that gas-water centrifuge capillary pressure data is consistent with oil-water and gas-water porous plate capillary pressure data.
- Showed that mercury injection capillary pressure data.
- Should be validated before it can be used reliably.
- Showed that extensive measurements provide the basis for reliable capillary pressure modeling.
- Recommend that alternate methods of P averaging should be evaluated to minimize uncertainty where less than an optimum number of measurements are available.

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