

# **EXPERIMENTAL MEASUREMENTS OF CAPILLARY PRESSURE AND RELATIVE PERMEABILITY HYSTERESIS**

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## **ABSTRACT**

Capillary pressure and relative permeability hysteresis have been investigated on core samples with different wetting characteristics. The relative permeability and capillary pressure curves depend on the direction of saturation changes and on the maximum and minimum achieved saturations. A conceptual model to explain the hysteresis trends in both the relative permeability and capillary pressure is presented. The model attributes hysteresis to a combination of 1) trapping of one phase by another, 2) contact angle hysteresis and 3) the wettability change of parts of the pore space after contact with crude oil.

In the literature there is a lack of a complete and consistent physical model to describe the hysteresis phenomenon due mainly to the fact that experimental data is rather scarce. Most of the available data is for water-wet systems. Therefore, there is a need for measurements done on non-water-wet systems. The data presented in this paper is measured on core samples of different wettability, i.e., water-wet and non-water-wet core samples. The measurements have been carried out on both carbonate and sandstone core material using Centrifuge, Steady State, CAPRICI and  $P_c$ -probe techniques.

The experimental data show that there is significant hysteresis in the capillary pressure between primary drainage, primary imbibition and secondary drainage curves especially for non-water-wet samples. Moreover, for non-water wet samples, the bounding imbibition (i.e., primary imbibition) and secondary drainage  $P_c$  curves do not form a closed hysteresis loop. This is observed in both the bounding and scanning curves. We also found that water relative permeability curves exhibited either very little or no hysteresis at all except when considerable part of the pore space became oil-wet. On the other hand, oil relative permeability curves showed strong hysteresis between the primary drainage and primary imbibition curves for all wetting status, with very little hysteresis thereafter except for mixed to oil-wet plugs. Experimental data suggests that while contact angle hysteresis has a profound effect on capillary pressure hysteresis, it hardly affects relative permeability hysteresis.

## **1. INTRODUCTION**

Capillary pressure and relative permeability curves depend on both the direction of saturation changes and on the maximum and minimum achieved saturations. There is no complete and consistent physical model to describe hysteresis due mainly to the lack of experimental data. Most available data is for water-wet systems. In this paper we will

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discuss both water-wet and non-water-wet systems. We have studied hysteresis in both relative permeability and capillary pressure curves using centrifuge, steady state, CAPRICI [1] and Pc-probe [2] techniques. The Pc-probe technique was recently developed which aims at direct measurement of the Pc curve.

Throughout this paper drainage will be used to describe oil displacing water process and imbibition will be used to describe water displacing oil process regardless of the wetting conditions of the rock. Moreover, primary drainage will refer to the oil displacing water process which starts at 100% water saturation, primary imbibition refers to water displacing oil which follows primary drainage. The primary imbibition Pc or relative permeability curve which starts at connate water and ends at residual oil is called a bounding imbibition curve while the drainage curve which starts at residual oil and ends at connate water is called bounding drainage curve. Drainage and imbibition curves which do not span between residual oil and connate water are referred to as scanning curves.

A conceptual physical model is presented which explains the observed hysteresis trends in both capillary pressure and relative permeability. In this model hysteresis in capillary pressure and relative permeability is attributed to three main factors:

- 1) Trapping of the displaced phase by the displacing phase
- 2) Contact angle hysteresis
- 3) Wettability changes

Trapping can be easily quantified by performing proper experiments where the trapped saturation can be measured as a function of the initial saturation. On the other hand it is not easy to quantify the effect of contact angle or wettability on hysteresis as to date there is no experimental procedure to directly measure contact angle or wettability during flooding experiment. Therefore, we will present a conceptual model which is capable of explaining the observed hysteresis trends in relative permeability and capillary pressure. Moreover, we propose a method to quantify the contact angle hysteresis and wettability changes from the observed hysteresis trends.

## **2. CONCEPTUAL HYSTERESIS MODEL**

### ***2.1 Trapping***

Let us first consider a water-wet porous medium that is 100% saturated with water. During drainage oil will first invade the largest pores. As the oil pressure increases smaller pores will be subsequently filled with oil and the oil saturation increases up to  $S_o^{\max}$ . In this drainage process no trapping of water occurs and both phases will be connected throughout the porous medium where oil is located in the center of the large pores and water is located in the small pores and as a thin layer on the rock surface. During imbibition oil will be trapped as isolated blobs in the center of the large pores due to snap-off. Oil will be trapped in the part of the pore space invaded with water during imbibition and therefore trapped oil will depend on the initial oil saturation. In secondary drainage process where oil starts to invade the porous medium, filled with water and residual oil, some of the residual oil will start to be connected and in this process no water is trapped. Hence in water-wet system it is only oil which can be trapped during

imbibition while it will be reconnected during subsequent drainage, no water trapping occurs.

Suppose now after the primary drainage the wettability of the rock changed to strongly oil-wet. During imbibition no oil will be trapped. However, water will now be trapped during the secondary drainage. In general, though, strongly water-wet and strongly oil-wet formations are rarely observed. Most likely the wettability of the rock upon oil invasion changes to mixed-wetness where part of the pore space is oil-wet and the other part is water-wet. In this case oil will be trapped during imbibition, and water will be trapped in the oil-wet part during the subsequent drainage. Trapping of oil and water is dependent on the wetting status of the porous medium. Therefore, using water-wet initial oil/residual oil ( $S_{oi}/S_{or}$ ) correlation in postulating hysteresis models for non-water-wet rock leads to erroneous results.

To help understanding how trapping affects capillary pressure and relative permeability we will introduce the terms effective mobile oil saturation  $S_o^*$  and effective water saturation  $S_w^*$  which are defined as:

$$S_o^* = S_o - S_o^{trapped} + S_w^{trapped} \quad (1)$$

$$S_w^* = S_w + S_o^{trapped} - S_w^{trapped} \quad (2)$$

For water-wet conditions  $S_w^{trapped}$  will be zero while for oil-wet porous medium  $S_o^{trapped}$  will be zero.

## 2.2 Contact angle Hysteresis

The contact angle between oil and water depends on the direction of saturation changes. Receding contact angle  $\theta_r$  (contact angle during oil flooding) is usually lower than advancing contact angle  $\theta_a$  (contact angle during water flooding). The difference in advancing and receding contact angles may cause a hysteresis in both capillary pressure and relative permeability. Contact angle hysteresis of up to  $90^\circ$  was observed in experiments [3]. As described later in this paper, experimental data suggests that the contact angle hysteresis has a significant effect on capillary pressure hysteresis while it hardly affects relative permeability hysteresis.

## 2.3 Wettability Change

As mentioned above, when oil invades the porous medium, it may rupture the thin film of water and comes in contact with the rock surface rendering the rock mixed or oil-wet. This change in wettability will affect the capillary pressure and relative permeability hysteresis. The wettability change will affect both contact angles and trapping of the displaced phase. It also may affect the filling sequence of pores during imbibition or drainage which will have important effect on the relative permeability of the rock.

## 2.4 Capillary Pressure Hysteresis

### 2.4.1 Water–Wet Rock

During primary drainage all the oil in the porous medium is mobile and the capillary pressure as a function of mobile oil is given by the drainage  $P_c$  curve. During imbibition the effective mobile oil saturation will be lower than the actual oil saturation (i.e., trapped and mobile oil) in the porous medium, see equation 1. Consequently, the primary imbibition  $P_c$  can be derived from the primary drainage  $P_c$  as follows:

$$P_c^{pi}(S_w) = P_c^{pd}(S_w + S_o^{trapped}) \quad (3)$$

where the imbibition capillary pressure at water saturation  $S_w$  is the same as the drainage capillary pressure at the effective water saturation  $S_w + S_o^{trapped}$ . This means for a given water saturation the  $P_c^{pi}$  curve is lower than the  $P_c^{pd}$  curve. The secondary drainage  $P_c^{sd}$  curve is also given by eq. 3, i.e, when there is no contact angle hysteresis and no wettability changes then both  $P_c^{pi}$  and  $P_c^{sd}$  curves are identical.

The effect of contact angle hysteresis on capillary pressure hysteresis can be easily quantified by substituting  $\mathbf{q}_r$  and  $\mathbf{q}_a$  in the capillary pressure definition.

$$P_c = P_o - P_w = \frac{\mathbf{s} \cos \mathbf{q}}{r} \quad (4)$$

$$\Delta P_c = P_c^{pi} - P_c^{pd} = \frac{\mathbf{s}(\cos \mathbf{q}_a - \cos \mathbf{q}_r)}{r} \quad (5)$$

where  $\mathbf{s}$  is the interfacial tension,  $\mathbf{q}$  the contact angle and  $r$  is the pore radius. The effect of contact angle hysteresis is to shift the imbibition  $P_c$  at the same water saturation downward compared to drainage  $P_c$  curve. For water-wet rock, the secondary drainage curve will still be given by eq. 3 as no contact angle hysteresis is expected between  $P_c^{pd}$  and  $P_c^{sd}$  curves. However, the primary imbibition  $P_c$  curve is calculated from the primary drainage curve as follows:

$$P_c^{pi}(S_w) = P_c^{pd}(S_w + S_o^{trapped}) + \frac{\mathbf{s}(\cos \mathbf{q}_a - 1)}{r} \quad (6)$$

where +1 is the cosine of zero receding contact angle during primary drainage. The subsequent imbibition and drainage  $P_c$  curves will be identical to the bounding imbibition and the secondary drainage curves, respectively. Figure 1 shows primary drainage, bounding imbibition and secondary (bounding) drainage curves for water-wet medium taking into account trapping and contact angle hysteresis.

From the above equation both  $S_{or} / S_{oi}$  correlation and the effective advancing contact angle can be easily calculated for water-wet porous medium if  $P_c^{pd}$ ,  $P_c^{pi}$  and  $P_c^{sd}$  curves are measured. The trapping function can be obtained by comparing the  $P_c^{pi}$  and  $P_c^{sd}$  curves

while effective contact angle is obtained by comparing  $P_c^{pi}$  and  $P_c^{sd}$  curves. On the other hand, if  $S_{or}/S_{oi}$  correlation is known we can still calculate the  $P_c^{sd}$  curve and the effective advancing contact angle. Using the bounding curves and trapping function we can calculate the scanning drainage and imbibition capillary pressure curves. For water-wet systems, as no water trapping is expected, bounding and scanning curves form closed hysteresis loops.

#### 2.4.2 Non-Water Wet Rock

For non-water wet systems wettability will introduce an extra hysteresis in capillary pressure. As discussed above wettability affects the capillary pressure in two ways.

Firstly, the contact angle will increase as compared to water-wet medium which will shift both imbibition and secondary drainage capillary pressure curves to lower values. Secondly, wettability will affect trapping of both oil and water. As the plug becomes less water-wet (or more oil-wet) the trapped oil will decrease and the trapped water during secondary drainage will increase. Consequently, an increase in connate water saturation  $S_{wc}$  at the end of the secondary drainage process is expected.

Similar to the water-wet case oil trapping and contact angle hysteresis will shift the  $P_c^{pi}$  and  $P_c^{sd}$  curve to lower water saturation. On the other hand, water trapping shifts both curves to higher water saturation relative to no water trapping case. Due to water trapping, the  $P_c^{pi}$  and  $P_c^{sd}$  curve (either bounding or scanning curves) do not form a closed hysteresis loop which is in contradiction with the assumption in most available hysteresis models.

From the above discussion, for non-water-wet rock, the  $P_c^{pi}$ ,  $P_c^{sd}$  and  $P_c^{si}$  are given as:

$$P_c^{pi}(S_w) = P_c^{pd}(S_w + S_o^{trapped}) + \frac{\mathbf{s}(\cos \mathbf{q}_{a(ow)} - 1)}{r} \quad (7)$$

$$P_c^{sd}(S_w) = P_c^{pd}(S_w + S_o^{trapped} - S_w^{trapped}) + \frac{\mathbf{s}(\cos \mathbf{q}_{r(ow)} - 1)}{r} \quad (8)$$

$$P_c^{si}(S_w) = P_c^{pd}(S_w + S_o^{trapped} - S_w^{trapped}) + \frac{\mathbf{s}(\cos \mathbf{q}_{a(ow)} - 1)}{r} \quad (9)$$

Where  $\mathbf{q}_{a(ow)}$  and  $\mathbf{q}_{r(ow)}$  are the advancing and receding contact angles of the oil-wet medium (the medium after changing wettability). The subsequent drainage/imbibition  $P_c$  curves will follow the secondary drainage/imbibition curves. The second term in the above equations represent both wettability and contact angle contribution to capillary pressure hysteresis. Due to contact angle hysteresis the rock may behave as oil-wet during imbibition and as water-wet during secondary drainage. This is what we often observe in capillary pressure curves, i.e., the imbibition capillary pressure is negative while the secondary drainage capillary pressure is positive.

Calculating scanning curves from the bounding curves is not straightforward as for the water-wet case. When an imbibition process starts at intermediate water saturation the

wettability of the rock may be different than the wettability of the same rock when the imbibition starts at connate water. Therefore, the effect of wettability on scanning curve hysteresis is different than that on bounding curve hysteresis. Consequently, measuring the bounding  $P_c$  curves and trapping functions may not provide enough input to calculate scanning curves. Wettability is a factor which affects the scanning curve starting at a certain initial oil saturation but wettability itself maybe a function of initial oil saturation. This is going to be a limitation in any hysteresis model which tries to predict scanning curves from measured bounding curves.

## 2.5 Relative Permeability Hysteresis

Hysteresis in relative permeability will be treated in a separate paper; however, we will here introduce the relative permeability hysteresis model and in Section 3.2 we will report some experimental observation on relative permeability hysteresis.

### 2.5.1 Water-wet Rock

Similar to capillary pressure, the relative permeability of each phase as a function of the mobile saturation is given by the drainage relative permeability curves. The effect of oil trapping on imbibition  $k_{ro}$  and  $k_{rw}$  is given by equations 10 and 11:

$$k_{ro}^{pi}(S_w) = k_{ro}^{pd}(S_w + S_o^{trapped}) \quad (10)$$

$$k_{rw}^{pi}(S_w) = k_{rw}^{pd}(S_w + S_o^{trapped}) - g(S_w) \quad (11)$$

The first term in the above equations shows the change in the imbibition relative permeability due to trapping of oil. The effective mobile oil saturation is lower than the actual oil saturation and that shifts both imbibition  $k_{ro}$  and  $k_{rw}$  to lower water saturation compared to drainage relative permeability curves. The second term in equation 11 is a vertical shift (downward) of the water relative permeability. This reduction in water relative permeability is caused by the fact that trapped oil occupies the center of the big pores where water is moving, thus it hinders the movement of water and reduces its relative permeability. Therefore, oil trapping reduces imbibition  $k_{ro}$  while it acts in two opposite directions on imbibition  $k_{rw}$ . In principle imbibition  $k_{rw}$  can be higher or lower than drainage  $k_{rw}$  depending on which effect is stronger. Both effects may cancel each other which may explain why water relative permeability in water-wet rock does hardly experience any hysteresis. It is well possible that at high water saturation and due to the fact that more oil is trapped in the big pores, imbibition water relative permeability will be lower than the drainage one.

In secondary drainage, oil will start displacing water from big pores and will follow the same route as bounding imbibition. As no water will be trapped the secondary drainage relative permeability curves will follow the bounding imbibition curves and no hysteresis is expected anymore due to trapping. Any measured hysteresis between secondary drainage and bounding imbibition relative permeability curves will be caused by contact angle hysteresis. However, measurements suggest that contact angle hysteresis has hardly any effect on relative permeability hysteresis as we do not measure any hysteresis

between imbibition and secondary drainage relative permeability curves for both oil and water. Therefore, in water-wet rock trapping of oil is the only cause for hysteresis.

### **2.5.2 Non-Water Wet Rock**

For non-water-wet rock, wettability will introduce extra hysteresis in relative permeability. The change in wettability will affect 1- trapping of oil and water, 2- the sequence of pore filling during imbibition and secondary drainage and 3- the distribution of both phases on the microscopic scale. Oil trapping will have the same effect as for the water-wet rock. The imbibition  $k_{r_o}$  and  $k_{r_w}$  will be given by equations 10 and 11 but now trapping functions will be different. In the secondary drainage, water will be trapped in the oil-wet part of the rock and that shifts the secondary drainage curves to higher water saturation. This means secondary drainage  $k_{r_w}$  will be reduced while secondary drainage  $k_{r_o}$  will be enhanced compared to the imbibition relative permeability curves. Trapped water will also hinder the movement of oil and reduce the secondary drainage  $k_{r_o}$ .

The sequence of pore filling in a non-water-wet rock is different when compared with the drainage process in strong water-wet rock. In non-water-wet rock water, during primary imbibition, starts to displace oil from the small water-wet pores and the big oil-wet pores. Therefore, for a given water saturation, water occupies more big pores during imbibition than during primary drainage [4]. Thus imbibition  $k_{r_w}$  will be shifted up compared to primary drainage  $k_{r_w}$ . For oil, using the same reasoning, the imbibition  $k_{r_o}$  will be shifted down compared with the drainage  $k_{r_o}$  as now there are fewer large pores occupied with oil. In the secondary drainage, oil starts to displace water from the small oil-wet pores and the big water-wet pores. Therefore at a given water saturation, oil will occupy more big pores than in primary imbibition but less big pores than in primary drainage. Consequently, the oil relative permeability is higher in the secondary drainage than primary imbibition but lower than in primary drainage. Conversely, water relative permeability is lower in secondary drainage than in primary imbibition but higher than that in primary drainage.

The wettability changes during aging will result in redistribution of both phases on the microscopic scale (i.e., oil will become in contact with the pore surface in the oil-wet part while the water film will move towards the center of the pores). This saturation redistribution will reduce oil relative permeability since oil is now moving on the surface of the rock while before aging the water film was acting as lubricant to the oil phase. On the other hand, oil will act as lubricant for water in the oil-wet part of the rock which will enhance water relative permeability. This means that if oil flooding is resumed, after aging the plug at connate water, the oil relative permeability end point will decrease compared to the value at the end of primary drainage. This is in contrast with all existing hysteresis models which assume that the oil relative permeability end points (or the permeability of oil at the beginning of scanning curves) should originate from the primary drainage curve.

While it is conceptually possible to, at least qualitatively, understand the effect of each of the above factors on water and oil relative permeability hysteresis, it is hard to predict the over all effect. As explained in the discussion some factors will act to enhance hysteresis

whereas some act to reduce hysteresis. Experimental data will help describe which factor is stronger depending on the nature of observed hysteresis.

### 3. EXPERIMENTAL DATA

#### 3.1 Capillary Pressure Data

Figure 2 shows drainage and imbibition bounding curves measured on 6 different low permeable limestone samples. Figure 3 shows drainage and imbibition scanning curves measured on 4 more samples. All experiments started with 100% water saturated plugs, following the primary drainage the plugs were aged for four weeks at high pressure and temperature before starting the subsequent imbibition/drainage experiments. The data shown in Figure 2 is measured using a combination of centrifuge, CAPRICI and Pc-probe techniques while that data in Figure 3 is measured using CAPRICI and Pc-probe technique. A number of observations can be made:

- 1- The connate water in the secondary drainage is higher than that in the primary drainage due to the extra trapping during the secondary drainage experiment. An increase of 15 saturation units in connate water is sometimes observed. Note that in most cases the residual oil was less than 10 saturation units which shows that trapped water can be more than the trapped oil.
- 2- All samples exhibit significant hysteresis in both the bounding and scanning curves even when the loop does not span more than 10 saturation units.
- 3- The entry pressure for the secondary drainage is much lower than that of primary drainage due mainly to wettability changes.
- 4- The primary imbibition and the secondary drainage curves do not constitute a closed hysteresis loop as observed for water-wet samples [5], and references therein. This is an important observation which is not taken into account in most available hysteresis models, see [5-10] and references therein.
- 5- Similar to the bounding curves, the scanning curves do not form a closed loop. The drainage scanning curve does not end at the same water saturation as the imbibition scanning curve. A shift of 2-3 saturation units is observed.
- 6- A second loop starting at the same water saturation overlaps the first loop, which is now expected as we have no extra trapping any more.

The two examples in Figures 2e and 2f are used to calculate the contribution of each term on the capillary pressure hysteresis using equation 7-9. Oil and water trapping functions are needed to perform the calculations. The residual oil saturation was measured to be 5% and 7% and the trapped water saturation 8% and 14% saturation units, respectively. Trapping of the displaced phase (oil or water) was assumed to be linearly increasing as more of the pore space is invaded with the displacing phase, i.e., during imbibition trapped oil increases linearly as more of the pore volume is filled with water. Note that the trapped water is the extra water trapped during the secondary drainage experiment and not the total secondary drainage connate water. It is also important to note that the same pores have been accessed with oil during the primary and secondary drainage experiments. Due to water trapping we need now less amount of oil to fill the same pore volume. Therefore, every thing will be calculated as a function of water saturation during primary drainage.

Using equations 7-9 together with the measured  $P_c$  curves shown in Figures 2e and 2f we calculated  $P_c^{pd}(S_w+S_o^{trapped})$ ,  $P_c^{pd}(S_w+S_o^{trapped} - S_w^{trapped})$ ,  $\cos(\theta)_{a(ow)}$  and  $\cos(\theta)_{r(ow)}$ . The calculated effective contact angles are shown in Figure 4. The uncertainty of the calculated contact angles increases close to connate water and residual oil saturation. The effective advancing contact angle (during imbibition) is higher than  $90^\circ$  for most of the pore space and it increases as water saturation increases which is due to applying higher pressure to fill more pores with water. On the other hand, the effective receding contact angle is lower than  $90^\circ$  for all the pore space and decreases as more of the pore space is filled with oil. The contact angle hysteresis ( $\theta_{a(ow)} - \theta_{r(ow)}$ ) is between  $45^\circ$ - $50^\circ$  for sample 5 and  $25^\circ$ - $30^\circ$  for sample 6.

Note that while the primary drainage  $P_c$  plateau of sample 6 is a factor of 1.5 higher than that of sample 5 the primary imbibition plateau is the same. Taking the effect of trapping, wettability and contact angle hysteresis into account may explain why the imbibition  $P_c$  curves do not necessarily scale with permeability similar to primary drainage curves.

### 3.2 Relative Permeability Data

Hysteresis in relative permeability will be treated in a separate paper; however, we will report few observations:

- 1- The oil relative permeability at connate water  $K_{ro}(S_{wc})$  varied considerably depending on the wettability of the sample. For strongly water-wet samples,  $K_{ro}(S_{wc})$  was some times higher than 1. For mixed-wet samples  $K_{ro}(S_{wc})$  varied from about 0.8 (small part of the pore space was exposed to crude oil) to less than 0.5 (large part of the pore space exposed to crude oil). Samples which showed even more oil-wet characteristics had an oil relative permeability end point of 0.2.
- 2- The water relative permeability end point at residual oil saturation  $K_{rw}(S_{or})$  increased as oil-wetness increased,  $K_{rw}(S_{or}) \sim 0.1$ - $0.3$  for the water-wet plugs and  $\sim 0.8$  for samples which showed oil-wet behavior.
- 3- For a number of samples we observed no hysteresis in both oil and water relative permeability between the bounding imbibition and subsequent drainage and imbibition, while there is considerable hysteresis between the primary drainage and bounding imbibition oil relative permeability curves. This is an indication that while contact angle hysteresis had a profound effect on capillary pressure hysteresis it hardly affects relative permeability hysteresis. In some cases hysteresis between secondary drainage and primary imbibition was observed for those samples showing more mixed-wet to oil-wet characteristics. The cause for such hysteresis is believed to be the sequence of pore filling as discussed earlier.
- 4- Water relative permeability showed very little hysteresis and sometimes the primary imbibition curve was lower than the primary drainage curve especially at high water saturation, which is believed to be due to the fact that residual oil is now hindering the movement of water. The wettability of the plugs changed upon aging with oil but still very little hysteresis is observed in the water relative permeability. Hysteresis in water relative permeability is only observed when the plug shows more oil-wet characteristics.

## CONCLUSION

- 1- A conceptual hysteresis model is presented which explains most of the observed trends in capillary pressure and relative permeability hysteresis. The model attributes hysteresis to three main factors, trapping, contact angle hysteresis and wettability changes.
- 2- Unlike most available hysteresis models we found that, for non-water-wet rock, the bounding imbibition and secondary drainage capillary pressure curves do not form a closed hysteresis loop, the same is being observed in the scanning loops. Connate water increase of up to 15 saturation units is observed between the primary and secondary drainage for mixed-wet systems.
- 3- Using the model presented in this work an effective contact angle (both receding and advancing contact angles) as a function of saturation can be calculated when the primary drainage, primary imbibition, secondary drainage and secondary imbibition capillary pressure curves are measured together with the water and oil trapping functions. Two examples were presented where contact angle hysteresis of  $25^\circ$  in one case and  $45^\circ$  in the other case was observed.
- 4- Oil relative permeability end point at connate water varied considerably with wettability. Oil-wet plugs showed an oil relative permeability end point as low as 0.2 while water-wet plugs had an oil relative permeability end point higher than 1. Water relative permeability end point increased as the plugs became more oil-wet.
- 5- No hysteresis is observed between the bounding imbibition and the subsequent drainage and imbibition curves of both oil and water relative permeability curves for most of the plugs studied in this work. Hysteresis was only observed when the plugs showed more oil-wet characteristics.
- 6- Contact angle hysteresis has a profound effect on capillary pressure hysteresis but it hardly affects relative permeability hysteresis.
- 7- Work is ongoing to calculate scanning curves from bounding curves.

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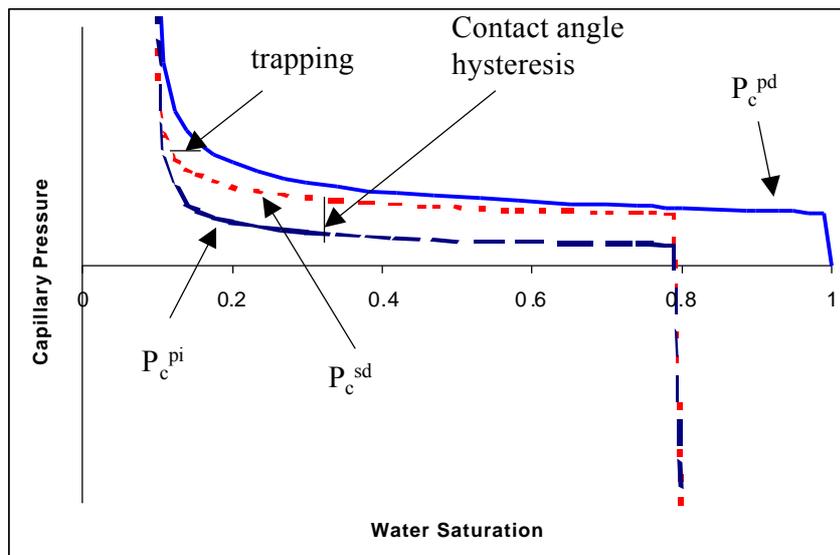


Figure 1: Capillary pressure hysteresis in water-wet medium.

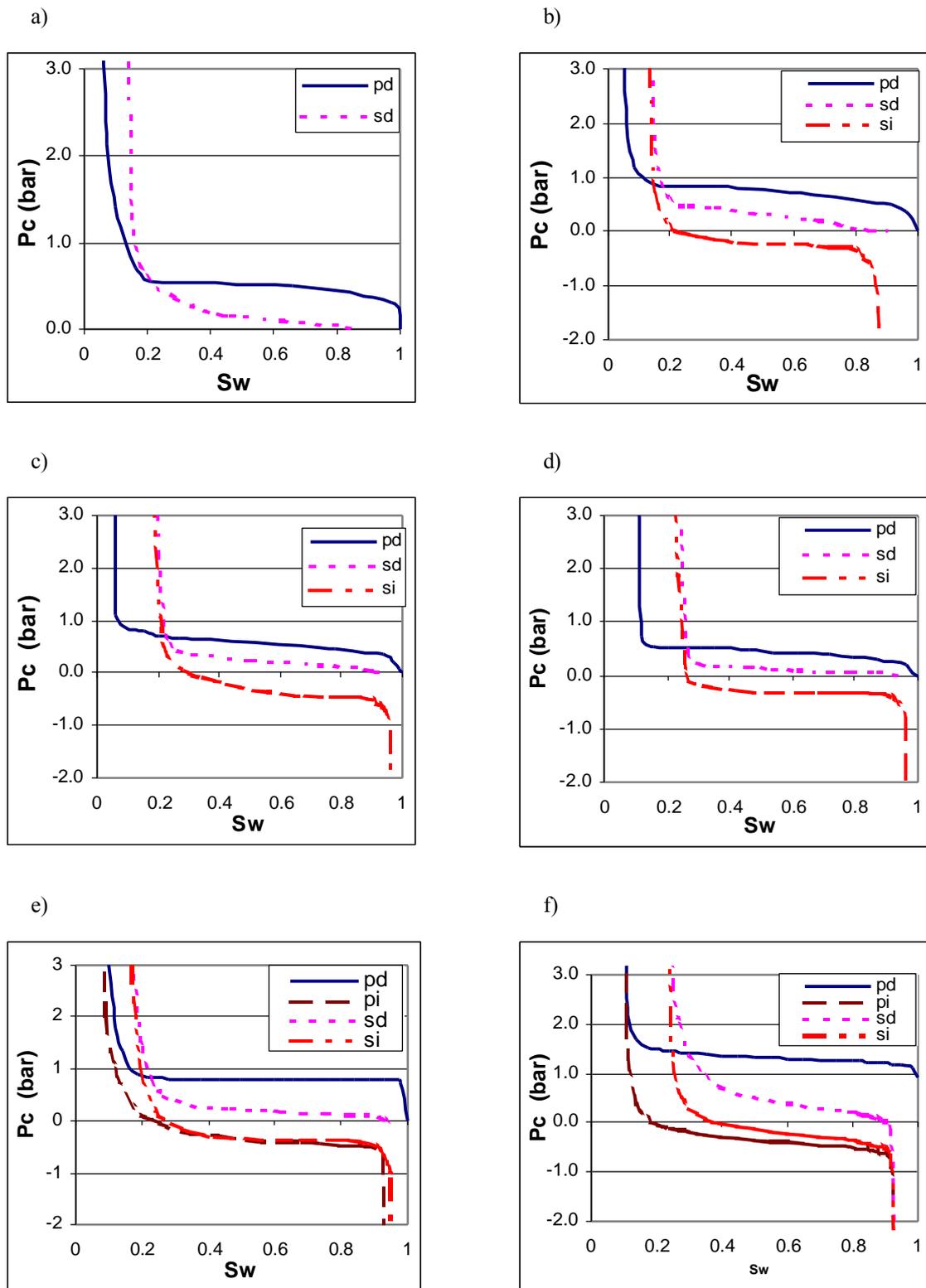


Figure 2: Capillary pressure hysteresis measured using centrifuge technique, the positive imbibition part is measured using CAPRICI/Pc-probe techniques on plugs from the same formation, (pd: primary drainage, pi, primary imbibition, sd, secondary drainage, si secondary imbibition).

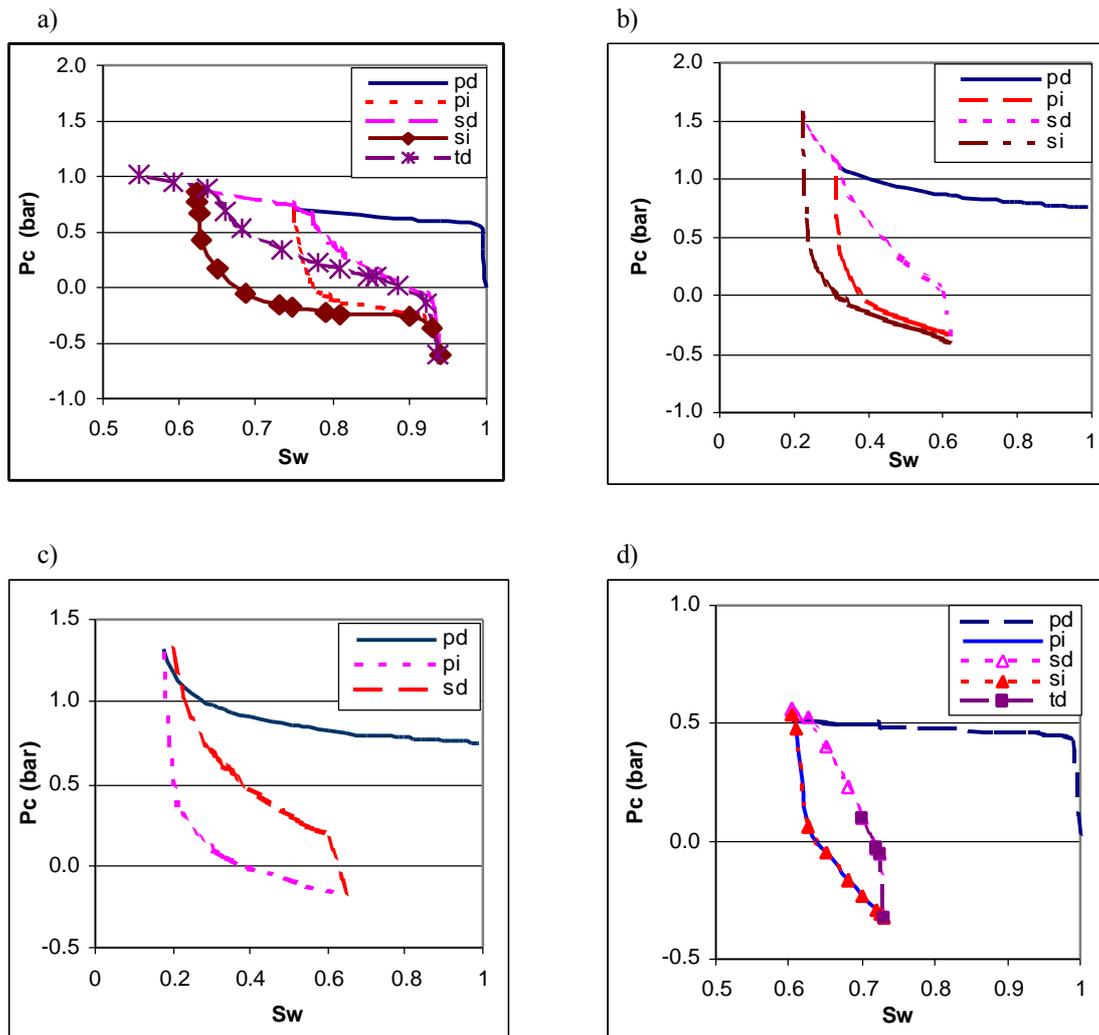


Figure 3: Capillary pressure scanning curves measured using using Caprici/Pc-probe techniques on plugs from the same formation (pd: primary drainage, pi, primary imbibition, sd, secondary drainage, si secondary imbibition, td third drainage).

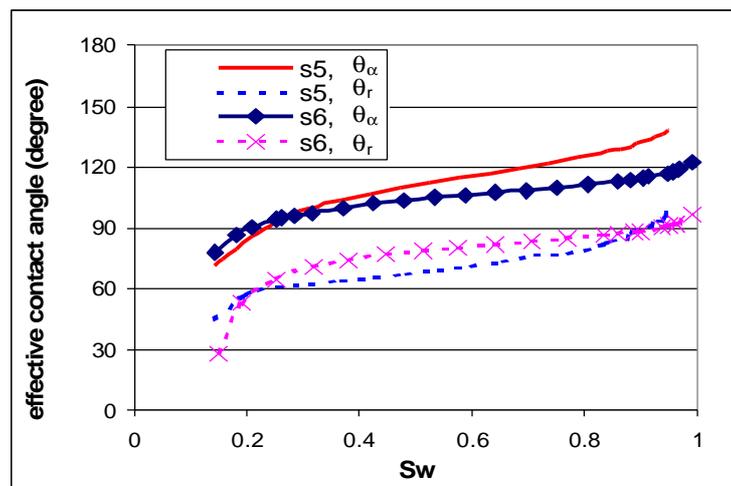


Figure 4: Effective contact angles calculated for samples shown in figure 2e and 2f.