EVALUATION OF THE CAPILLARY END EFFECT IN WATER-OIL PERMEABILITY TESTS USING THE TECHNIQUE OF MULTIPLE FLOW RATES

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ABSTRACT

The relative permeability curves obtained in the laboratory are used in reservoir simulators to predict production and decide the best strategies for an oil field. Therefore, researchers are studying several procedures to obtain relative permeability curves, among them the multiple flow rates injection methods. Thus, this work proposes to develop an experimental procedure with multiple increasing flows. To make this feasible, simulations were initially carried out at CYDAR, aiming to establish the flow rates and necessary the time to system stabilization, within the limits of the equipment. After that, the tests were carried out and the results obtained were the minimum time of 5 hours to stabilize the oil production and the differential pressure at each flow rate. The accounting and minimization of the capillary end effect in these tests were also evaluated. And the capillary pressure constraints contributed to minimize the number of possible solutions of the optimization problem improving the uniqueness of solution.

KEYWORDS
Relative Permeability, multiple flows rates, CYDAR, capillary end effect.

1 INTRODUCTION

Relative permeability is one of the most important data for reservoir engineering. The relative permeability curves obtained in the laboratory are used in reservoir simulators to predict oil production and decide the best strategies when exploring an oil field (CRUZ, 2015).

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The tests to obtain these curves, in a water-oil system, are performed on rock samples from the reservoir or on representative outcrops. These are often subjected to displacement tests in an unsteady-state regime, in which an attempt is made to repeat the fluid displacement processes that take place in the oil reservoirs during secondary recovery activities. In the test, capillary and viscous forces act in the rock sample, as well as in the petroleum reservoirs (AL-MJENI *et al.*, 2011; CRUZ, 2015).

Usually, this experiment is conducted by injecting water at a single constant flow rate. The experimental data obtained (differential pressure and produced volume of oil) is treated by analytical techniques, such as that of JBN (Johnson *et al.,* 1959), or by history matching, to obtain the parameterized relative permeability curves (K_r).

However, these tests have limitations and conditions that are intrinsic to the laboratory, differently from what occurs in real reservoir flows, such as the capillary end effect. This happens due to a discontinuity in capillary pressure at the end sample outlet, causing an erroneous residual oil saturation (GUPTA & MALONEY, 2016; HADLEY & HANDY, 1956).

Besides, many mathematical methods used to infer the K_r, as the JBN, do not consider the capillary forces, and the method of history matching does not guarantee the uniqueness of solution if used in experiments with only one injection flow rate. This can generate bias in the relative permeability obtained in the laboratory (UCAN *et al.*, 1997).

In the exposed context, the present work proposes to develop an experimental procedure of multiple flow rates, to obtain the relative permeability curves, based on the theoretical methodology proposed by Lenormand & Lenormand (2016).

The greatest advantage of this method is the accounting of the oil that was retained in the sample due to the capillary end effect. Furthermore, there is the possibility of determining both the capillary pressure (P_c) and relative permeability (K_r) in a single experiment and also to add a capillary pressure constraint to improve the uniqueness of the history match process.

2 RELATIVE PERMEABILITY EXPERIMENTS

During the drilling process of reservoirs, rock cores are extracted and undergo several laboratory tests to determine properties of relevance for oil extraction, such as porosity, permeability, and capillary pressure. Laboratory experiments must be carried out at reservoir conditions so that the results obtained are representative of the field.

In Figure 1, one of the most used coreflooding experiments to determine the K_r is presented, it is called the unsteady state relative permeability. The UnSteady-State (USS) method consists of displacing the fluid that saturates the porous medium by injecting another fluid at constant flow or constant pressure (RIOS *et al.*, 2012).

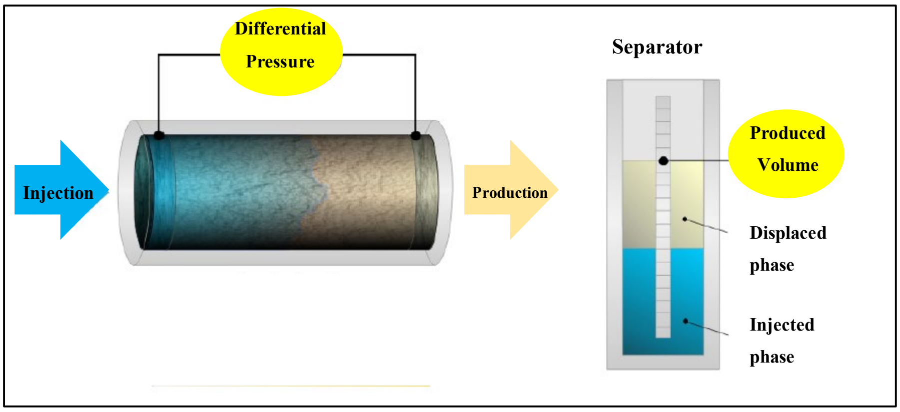

Figure 1. Scheme of the relative permeability test in transient regime (adapted from AMBRUS *et al.*, 2004).

For a water-oil system, an oil-saturated core with immobile water (S_{wi}) is first accommodated in the holder. This condition is representative of the initial state of the reservoir before the injection of fluids for its exploitation. Then, it is performed a water injection in the inlet face, while oil is produced at the outlet face. During the test, the produced oil volume and the differential pressure across the core are recorded.

The most used laboratory procedures in the water-oil relative permeability tests consists of the injection of water at a single flow rate, obtaining the residual oil saturation (*Sor*). The S_{or} can be greatly affected by the capillary end effect (BAUGET *et al.,* 2012). Thus, to minimize laboratory artifacts, a sudden increase in flow rate (bump flow) is performed at the end of the test. There is often an additional production of oil-related to the increase in differential pressure caused by the bump flow (CRUZ, 2015).

For identification purposes, the residual oil saturation (S_{or}) will be called remnant S_{or} (S_{or}^{rem}) when it is obtained in a test with only one injection rate and bump S_{or} (S_{or}^{bump}) when there is an increase in flow rate (bump flow).

3 CONVERTING LABORATORY DATA TO RELATIVE PERMEABILITY

The relative permeability curves are inferred from the differential pressure and oil production data collected in these tests. The solution techniques normally applied are analytical solutions, such as JBN (JOHNSON *et al.*, 1959) and Jones & Roszelle (1978), based on the Buckley-Leverett model for the displacement of immiscible fluids.

This method assumes simplifications such as one-dimensional flow, negligible capillary pressure, and homogeneous porous medium. These simplifications hardly represent the reality of the displacement tests performed in the laboratory (AMBRUS *et al.*, 2004; VIEGAS, 2017).

Another technique very used is the history matching (Rosa *et al.*, 2006), which is a non-linear regression problem. The procedures of this nature use parameterized K_r curves in a numerical flow simulator and an optimization process finds the parameters that best represent the experimental data. In this type of technique, the flow model can be simplified or not.

The advantage of this method is the possibility of including all effects that may be relevant in the actual displacement process, such as capillary pressure, medium heterogeneity, fluid compressibility, or gravity (AMBRUS *et al.*, 2004; WANG, 2014). However, many software that uses the non-linear regression method do not include these effects in the theoretical model, analyzing the data up to S_{or}^{rem}, as in JBN (CRUZ, 2015).

4 MULTISTEP PROCEDURE

The multiple flow rates test should be considered over the traditional one (single flow rate plus bump flow), even if that lasts longer than this. Because the experiments in several increasing flow rates provide K_r and P_c curves simultaneously (BAUGET *et al.*, 2012).

In the technique proposed by Lenormand & Lenormand (2016), the test is started by injecting water into the sample at constant flow until the oil production and differential pressure stabilize. Then, the flow rate is increased until the new stabilization is achieved. This process is repeated using 5 to 10 steps of injection rates. With each rate, additional oil is produced and the average water saturation increases. With these data, it is possible to account for the capillary end effect and the amount of oil that was retained due to this phenomenon. At the end of the test, S_{or}^{rem} is expected to be closer to the real S_{or} (GUPTA & MANOLEY, 2016).

5 MATERIALS AND METHODS

5.1 MATERIALS

The rock samples used were homogeneous outcrops of the Berea Buff formation, obtained from Kocurek Industries. To minimize the influence of the type of sample in the tests, the same 20 cm core was split into smaller cores, approximately 5 cm each. The basic properties of these samples are shown in Table 1.

Table 1. Properties of the sample and fluids used in the USS experiment multiple flows.

Sample	Length L (cm)	Diameter D (cm)	Absolute permeability K_{abs} (mD)	Porosity ϕ (frac.)	Porous Volume V_P (cm³)
Sample 1	4.78	3.82	597	0.225	11.99
Sample 2	4.84	3.82	602	0.227	12.24
Sample 3	4.9	3.82	601	0.228	12.5

The fluid used as the oil phase was the EMCA PLUS 70 and as the aqueous phase, a brine with a composition equivalent to that of the Brazilian Pre-Salt fields was used. The physico-chemical properties of fluids under test conditions are shown in Table 2.

Table 2. Physico-chemical properties of fluids at 21°C and ambient pressure.

Fluid	Density ρ (g/cm³)	Viscosity μ (cP)
Oil	0.856	23.0
Brine	1.142	1.48

5.2 METHODS

The USS water-oil relative permeability experiment at laboratory scale (Figure 2) followed the sequence of procedures proposed by Viegas (2017):

1. Cleaning the sample in Soxhlet apparatus, using methanol and methylbenzene (toluene).
2. The routine core analysis to obtain the basic properties of the samples, such as absolute permeability and effective porosity.
3. Total saturation of the samples with the brine of composition equivalent to the water of formation of the fields of the Brazilian Pre-Salt.
4. Centrifugation of samples in an oil environment to obtain irreducible water saturation (S_{wi}).
5. Accommodation of the core sample on a hydrostatic confinement cell, using 1,000 psi of confining pressure.

6. Measurement of effective oil permeability at irreducible water saturation ($K_{ro}@S_{wi}$).
7. Displacement of mineral oil by injection of brine to the state of residual oil saturation (S_{or}), with monitoring of oil production (N_P) and differential pressure (ΔP):
    - 7.1. With a constant flow of 1 cm³/min plus a bump flow of 4.0 cm³/min in the traditional test.
    - 7.2. With five flow levels in the multistep test: 1.0, 2.0, 4.0, 8.0 and 10 cm³/min.
8. Measurement of effective water permeability in S_{or};

The experimental data was used to estimate the relative permeability and capillary pressure by history matching. The software CYDAR® was used to estimate the parameters of the used models: LET model (Lomeland *et al.*, 2005) for relative permeability and $\log(S^{\beta})$ model (CYDAR User Manual, 2018) for capillary pressure.

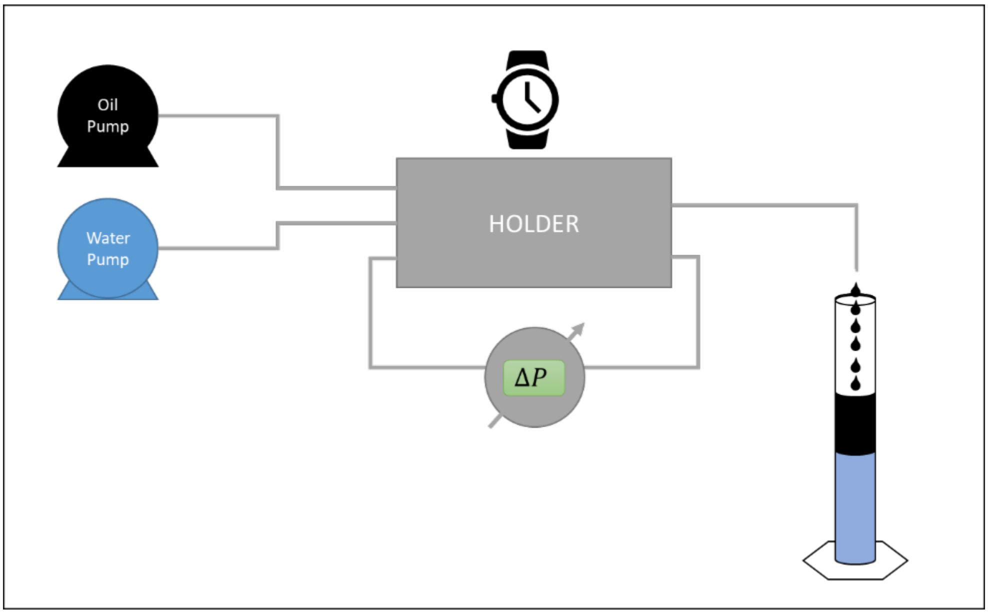

Figure 2: Schematic diagram of the relative permeability equipment under laboratory conditions.

6 RESULTS AND DISCUSSION

Figure 3 shows the experimental data from Sample 1, in which water was injected at a flow rate of 1.0 cm³/min for 23 hours. At the end of this first injection, 6.25 cm³ of oil was produced. The bump flow, with a flow rate of 4 cm³/min, was carried out afterward and the ΔP stabilized after 1 hour and there was no additional oil production. Returning to a flow rate of 1.0 cm³/min, the ΔP stabilized after 30 min. Thus, the traditional test with the bump flow was completed in 24.5h

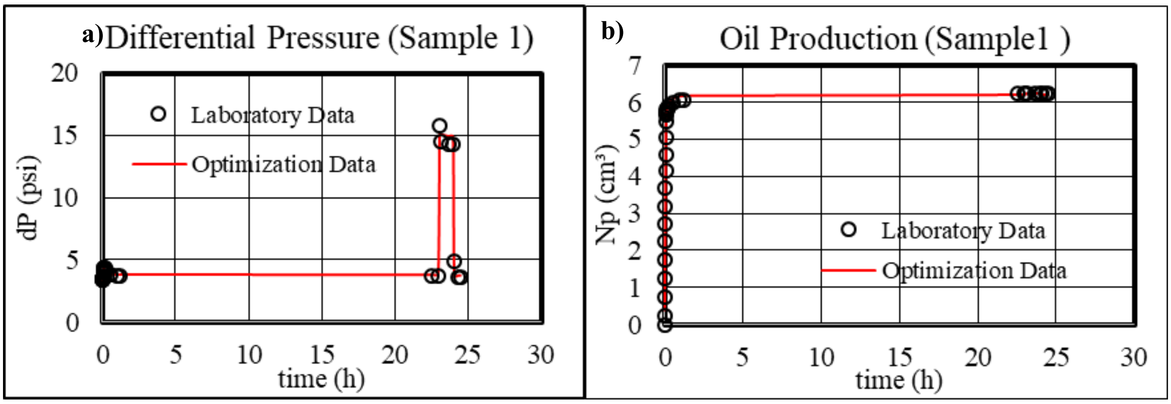

Figure 3: Experimental data obtained in the traditional water-oil relative permeability test with bump flow (points) and data obtained by the history-matching process (solid line) to obtain Kr and Pc curves. a) Differential pressure *versus* time. b) Volume of produced oil *versus* time.

Figure 4.a shows the capillary pressure curve estimated for the imbibition test. As shown by Abdallah *et al.* (2007), the sample showed results from a water-wet sample, where the capillary pressure remains positive during most of the saturation range, as shown in Figure 4.a Thus, water saturation preferably increases first in the smallest pores, due to wetting forces, so the displacement occurs from the smallest to the largest pores, and the water increasingly occupies the throat of pores that were previously filled with oil, as shown in Figure 4.b, which presents the relative permeability.

According to Masalmeh (2012), water-wet samples have very well-defined residual oil saturation and are insensitive to the flow rate, that is, S_{or} is not affected by the increased flow rate. Analyzing Figures 3 and 4, it is possible to infer that the sample is water-wet, so there was no additional production associated with bump flow, so S_{or}^{rem} was equal to S_{or}^{bmup}(Figure 3.b).

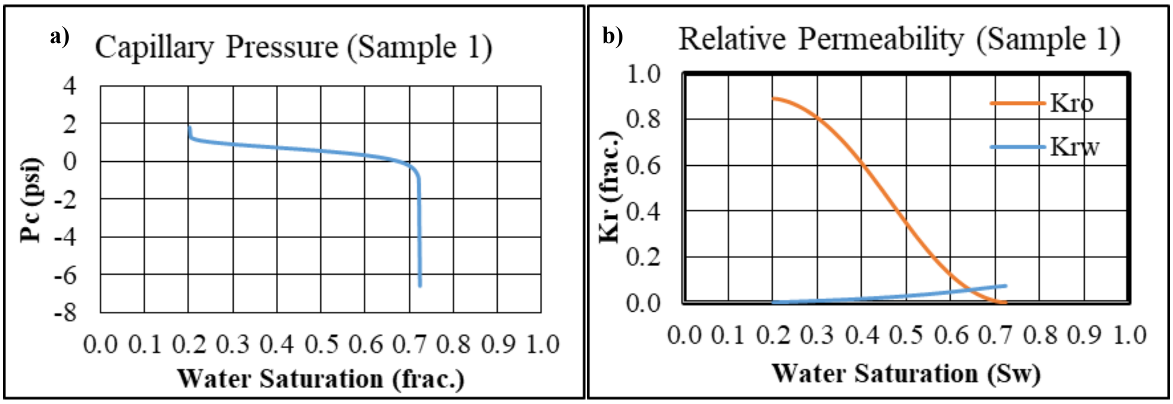

Figure 4: Curves estimated in CYDAR, using history matching. a) Capillary pressure curve as a function of water saturation. b) Relative permeability curves as a function of water saturation.

In Figure 5, the data of Sample 2 and Sample 3 are presented, which were submitted to the multistep process. In Figure 5.a it is identified that in the first test flow the Sample 1, 7.80 cm³ of oil was produced, and at the end of the 30 hours test, 7.93 cm³ had been produced, that is, even increasing the flow 10 times, there was a gain of only 1.7% in the volume of fluid produced about a flow of 1.0 cm³/min.

While in Sample 3, shown in Figure 5.b, the first flow of 1.0 cm³/min produced 7.25 cm³ during the initial 5 hours, ending the test with 7.50 cm³ of displaced oil. Thus, the 10-fold increase in flow provided a small gain of 3.4% of the oil produced about the initial flow.

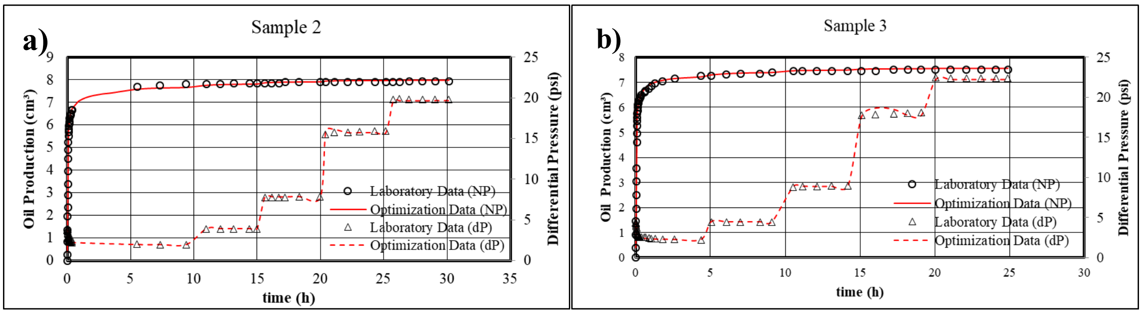

Figure 5: Experimental data obtained in the multi-step water-oil relative permeability test (points) and data obtained by the history-matching process (solid line) to obtain Kr and Pc curves. a) Sample 2. b) Sample 3.

The capillary pressure and relative permeability curves, presented in Figure 6 and Figure 7, fitted the experimental data with precision, as shown in Figure 5. In Figure 6, the P_c curves are positive in most of the water saturation range, representing water-wet samples. Also, adapting the calculation of the USBM index for the imbibition test, which measures the wettability using the areas under the positive and negative capillary pressure curves, this water wettability is confirmed, since the results are values greater than 1 (ABDALLAH *et al.*, 2007).

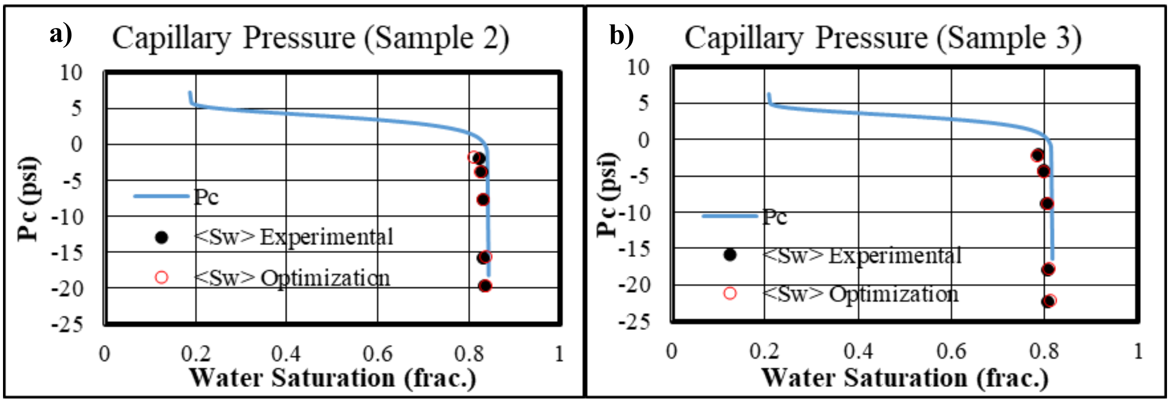

Figure 6: Capillary pressure estimated by history matching versus experimental average water saturation and optimized average water saturation. a) Sample 2. b) Sample 3.

Besides, interpreting the K_r curves in Figure 7, it is noticed that water begins to enter the smaller pores first, and as the water saturation increases, the pores are filled sequentially from the smallest to the largest, as well as a preferably wettable sample. water, as explained by Crotti (2008).

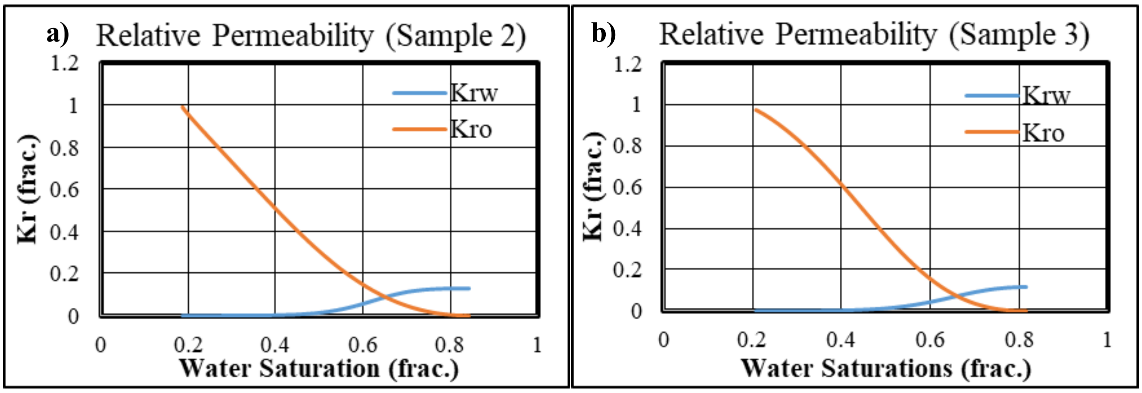

Figure 7: Relative permeability estimated by history matching as a function of water saturation. a) Sample 2. b) Sample 3.

The average water saturation $\langle S_w \rangle$ versus capillary pressure data presented in Figure 6 was obtained by the procedure proposed by Lenormand & Lenormand (2016). This procedure assumes that at the end of each flow rate, as oil production stops, the oil phase is not moving, therefore the differential pressure for this phase equals to zero. This implies that the differential pressure measured across the sample is the water phase differential pressure (Figure 8 and Equation 1). In Equations 2 and 3 it is demonstrated how these calculations are performed.

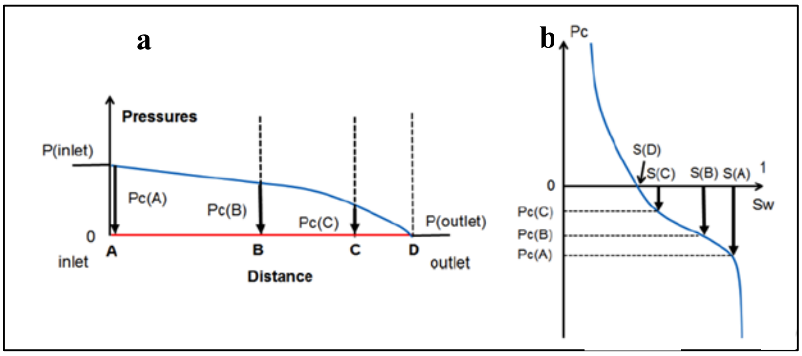

Figure 8: USS displacement. a) Pressure profile at equilibrium (water in blue and oil in red). The arrows represent the capillary pressure in different positions across the sample length. b) Determination of the correspondent water saturation in the capillary pressure curve (Lenormand e Lenormand, 2016).

$$P_w = \Delta P$$ Equation 1

$$P_c = P_o - P_w = 0 - \Delta P$$ Equation 2

$$P_c = -\Delta P$$ Equation 3

This data points of P_c vs $\langle S_w \rangle$ were used in CYDAR as an experimental constraint to the estimated capillary pressure, improving the solution uniqueness problem, faced in history matching process. Comparing the experimental and estimated data it is possible to conclude that the constraint was satisfied with great precision.

Saturation profiles at the end of each flow rate were also obtained by the history-matching process (Figure 9). It is possible to notice that the increase in flow rates causes an increase in the average water saturation, and consequently an additional oil production, as shown also in Figure 5.

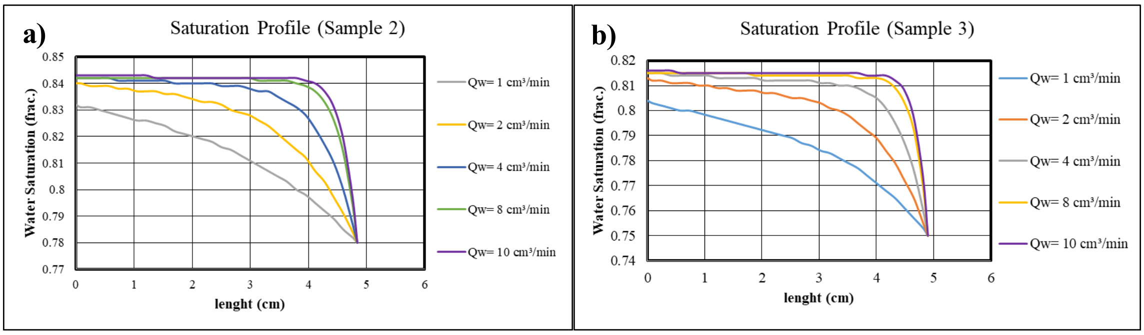

Figure 9: Saturation profile at the end of each flow. a) Sample 2. b) Sample 3.

Also, the saturation profiles become more uniform along the length of sample as the flow increases. In Figure 9, it is possible to observe that oil is trapped at the end of the core sample, thus there is a wettability to oil and these samples are mixed-wet (PETERS, 2012).

7 CONCLUSIONS

From the relative permeability experiments carried out, in three sandstone samples of the same petrophysical properties, but comparing different methodologies – Sample 1 with conventional test; Samples 2 and 3 with multiple flow rates - it is possible to conclude that:

- In high permeability water-wet samples the stabilization of the differential pressure and produced volume is achieved in 5 hours, at each imposed flow rate.
- Multiple flow rates methodology can minimize and account for the capillary end-effect, since there is additional production after the first flow, even if minimal.
- The relative permeability and capillary pressure curves obtained simultaneously in the same experiment reduce the problem of non-uniqueness of the solution, associated with the non-linear regression calculations applied in the historical adjustment.

8 ACKNOWLEDGMENTS

The authors gratefully acknowledge the support provided by CENPES/PETROBRAS, LRAP/COPPE/UFRJ and CAPES.

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