DRAINAGE CAPILLARY PRESSURE AND RESISTIVITY INDEX FROM SHORT-WAIT POROUS PLATE EXPERIMENTS

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ABSTRACT

Reliable experimental capillary pressure and electrical properties as functions of saturation history are essential as inputs for static and dynamic modeling of a reservoir. The only technique that simultaneously gives both Pc and Sw-RI relationship as functions of saturation history, and does not rely on a model with underlying assumptions for calculation, is the standard equilibrium method. This is also known as the standard porous plate equilibrium method. The only disadvantage with this method is that it is time consuming caused by the low flux through the diaphragm (porous plate).

In this paper we present drainage capillary pressure curves and resistivity index measured on reservoir rock samples by the standard equilibrium method at pseudo reservoir conditions. In parallel with this, a sister plug set has been analyzed by interrupting intermediate capillary displacement pressures before reaching equilibrium, with the objective of establishing Sw-RI relationship much faster. The results show that it is possible to establish identical Sw-RI relationship with a time-saving factor of three for the carbonate rock type under study.

Saturation data could be fitted to an exponential decay model using nonlinear regression in order to derive accurate capillary pressure curves from short-wait porous plate measurements. In addition, the experimental results were supported by simulation with Sendra. This gave more confidence in the data and opened the way into more future investigations towards examining factors and optimized design of the interrupted capillary displacement pressure tests.

INTRODUCTION

The most reliable method that can simultaneously measure capillary pressure (Pc) and resistivity index (RI) as a function of water saturation is the standard equilibrium (Eqm) method known as the porous plate (PP). However, this method is quite time consuming, and that is why several methods like the membrane technique [1] and the continuous injection method [2] have been developed to speed up the establishment of these properties. Although these proposed methods can acquire data in a much faster time they have their own problems and drawbacks [3]. John Shafer and Patrick Lasswell [5] revised a modeling technique as first proposed by IFP [6] to speed up the collection of PP Pc by not waiting for capillary equilibrium at each Pc step.

In the present work, we measured primary drainage PcRI on reservoir rocks by establishing initial water saturation (Swi) using the PP setup but without attaining Eqm at each applied Pc step. We call this type of test "Short-Wait Porous Plate". Parallel to this, we measured PcRI by the standard Eqm PP method on sister plugs to compare the short-wait (SW) porous plate RI data with the standard Eqm method. Water saturation data from both data sets were analyzed using nonlinear regression for quality control and Pc derivation. Numerical simulation with Sendra was also employed in a step towards optimum experimental setup design and possible derivation of Pc and relative permeability curves.

EXPERIMENTAL MEASUREMENTS

Primary drainage (PD) experiments were carried out on 11 carbonate rock samples to measure PcRI at reservoir conditions using dead crude oil as the displacing fluid. Representative samples were selected based on X-ray CT scans, high pressure mercury injection (MICP) and Poroperm measurements. He porosity of the selected samples ranged from 27% to 32% and the brine permeability (Kw) varied from 100 mD to 600 mD (see figure 1). The samples were split into two sister-plug batches. One batch underwent standard Eqm PP experiments where Eqm was maintained at each Pc step. The other batch was designed to give fast RI data by the SW PP method. In this method, we do not wait for full stability at the intermediate Pc steps. At a given step, the desaturation process continues until some "non-equilibrium" saturation is reached determined by a predefined experimental design which we will suggest below.

EXPERIMENTAL RESULTS AND DISCUSSIONS

Resistivity Index

Figure 2 presents both Eqm and SW PP Pc curves. The SW PP data show higher Sw at the early Pc stages compared to the Eqm data. Some of the SW PP samples, however, gave lower Swi than the Eqm data because the selected SW PP plugs are of higher rock quality as can be seen in figure 1. Figure 3 presents comparison RI-Sw relationships from Eqm and SW PP experiments. The results clearly show that similar RI data are obtained from both methods and that RI data is valid whether Pc equilibrium is actually achieved or not. Both data sets show almost linear relations between RI and Sw. Non-linear relations may be observed with high production rates soon after a "high" Pc pressure change [5]. The SW PP measurements should be designed to avoid high production rates by keeping saturation change at capillary numbers ($N_{cap} = \mu v/\sigma$) lower than 10^{-4}. μ stands for viscosity, σ interfacial tension and v fluid velocity. The validity of RI data, independent of eqm Pc, is based on the fact that PD is mainly a piston-like displacement, where pores and throats are filled in order of increasing capillary entry pressures. Once a pore has been filled by oil, water still remains in the corners and crevices of the invaded pores, and hence water remains connected throughout the primary oil invasion. Production of water is always possible through wetting layers. Therefore, fluid trapping or isolated fluid fraction in primary drainage is not important as water in the corners ensures global connectivity [4]. This is a fundamental principle in primary drainage that makes the SW PP experiments theoretically valid that can yield representative Swi and RI data. Figure 4 shows RI data with time for all Pc steps on both batches. There is a time saving factor of three when using the SW PP as compared with the Eqm method. The SW PP tests can thus give the opportunity to shorten the time for the acquisition of RI-Sw data and therefore provide faster calibrating parameters for well log interpretation.

Capillary Pressure

Figure 5 and figure 6 present Eqm and SW PP oil-water primary drainage Pc curves versus scaled mercury injection data, respectively for the two samples indicated with circles in figure 1. The figures also show Pc data points predicted from an exponential decay model which will be discussed later. There is a reasonable match between the eqm PP Pc data and the corresponding mercury curve in figure 5. Whereas, in figure 6, there is a mismatch between the SW PP Pc and the MICP curve. The mismatch is caused by the designed experimental setup of the SW PP where Eqm is not established at the applied intermediate Pc levels. Due to the absence of fluid entrapment in primary drainage, correct Swi values are established if stability is attained at the final step as can be seen in figure 6 (The O/W Pc curve approaches the MICP curve at Swi).

Modeling Saturation Data

The derivation of Pc curves from SW PP experiments can, in principle, be achieved by modeling production data to predict equilibrium saturations (Sw_{eqm}) at each Pc step. Several attempts were made in the literature to predict equilibrium volumes by proposing models [5,6]. We choose to model the desaturation process by the following exponential decay equation:

$$Sw = a.\exp(-b.t) + c \qquad (1)$$

Sw stands for water saturation in a rock sample at any time t. ‘a’, ‘b’ & ‘c’ are constants which could be solved for using non-linear least square methods. The choice of equation 1 is not arbitrary. Similar exponential terms have been used in the literature as analytical solutions for the description of production data in porous media [5-7]. Equation 1, however, allows for direct calculation of Sw_{eqm} without the involvement of volumes. The constant ‘c’ is equal to Sw_{eqm} at infinite time t. ‘b’ is the constant decay parameter which is set to be equal to 1/tc, where tc is the characteristic time of desaturation. Equation 1 was used to model saturation data from the Eqm PP experiments and was found to predict ‘measured’ Sw_{eqm} reasonably well. Figure 5 is an example of a modeled Pc curve on sample#24 from the Eqm method. Equation 1 was then used to predict Pc curves from the SW PP measurements. Figure 6 shows the predicted Pc curve on sample#36 from the SW PP method. At the 2nd Pc step in both samples, no saturation data can be predicted because the desaturation process at that Pc step is linear (i.e. controlled by the porous plate). Further discussions on this can be found in reference [5]. We recommend that saturation curves should be measured while the SW PP experiment is running to ensure sufficient data has been collected which is reflected in the bend of the saturation curve. Hammervold and Skjaeveland [8] suggest that the acceptable error in the prediction of Sw_{eqm} should be less than 2%. The uncertainty in the value of 'c' (i.e. Sw_{eqm}), in equation 1, is given by the curve fitting program, and should be evaluated "on the fly" so that the pressure step is increased to the next level when the uncertainty in 'c' has reached the acceptable error. Figure 7 depicts modeling of saturation data by equation 1 on sample#63 which was used to predict Sw_{eqm} at each Pc step as seen in figure 6. Therefore, the SW PP experiments, in addition to the fast and reliable RI data, can provide fast Pc curves through modeling saturation data at each Pc step.

Modeling Resistivity Index Data

Equation 1 was used to model RI data during the SW PP experiments. The basis of this is the relationship between Sw and RI. It is assumed that changes in RI data could also be modeled similarly to changes in fluid saturations. In order to apply the same exponential decay equation, we choose to model 1/RI by using equation 2. 1/RI is the reciprocal of RI data measured at any time t. 'a', 'b' & 'c' are constants which could be solved for using non-linear least square methods. 'c' is equal to RI_{eqm} at infinite time t. 'b' is the constant decay parameter which is set to be equal to 1/tc, where tc is the characteristic time of 1/RI during desaturation. This will allow for the comparison of the characteristic time tc for both Sw and RI. Figure 8 presents modeling of 1/RI data by equation 2 on sample#63. Both figure 7 and figure 8 show the characteristic time at each Pc step except 2nd step due to insufficient data. Tc for Sw is higher than that for RI in all the steps. This indicates that changes in RI are faster than those in Sw during primary drainage.

$$\frac{1}{RI} = a.\exp(-b.t) + c \qquad (2)$$

Numerical Simulation

Some of the primary drainage porous plate experiments have been supported by Sendra simulations. Even though we reconciled the experimental production data, it has clearly been demonstrated and verified earlier [7] that we cannot generally determine unique relative permeability from these kinds of experiments alone. Additional information is required from supporting experiments like flooding experiments and/or single-speed centrifuge measurements.

CONCLUSIONS

1. Short-wait porous plate experiments gave identical RI-Sw relationships to the standard equilibrium porous plate method and thus can offer fast and reliable RI and saturation exponent "n" results.
2. The validity of the short-wait porous plate RI and "n" data was argued to be due to the absence of fluid trapping and hence isolated fluid saturation in primary drainage invasion processes.
3. Short-wait porous plate tests should be designed such that saturation curves are measured at each Pc step while the tests are running. It is recommended to wait until the "bending" is seen in the curve before the next step is increased.

4. Saturation curves were modeled by a suggested exponential decay equation which gave rise to the derivation of capillary pressure curves from the short-wait porous plate measurements.
5. RI data were modeled by the exponential equation which confirmed the relationships between RI and Sw data.
6. Comparisons of the characteristic times between RI and Sw suggested RI change was faster during primary invasion. This may lead to nonlinear and perhaps unrepresentative RI-Sw results if the pressure steps experience high Pc change.

REFERENCES

1. Longeron, D., Hammervold, W.L., and Skjæveland, S.M.: "Water-Oil Capillary Pressure and Wettability Measurements Using Micropore Membrane Technique," SCA-Paper 9426, presented at the SCA Symposium in Stavanger, Sept. 12-14, 1994.
2. Zeelenberg, H.P.W., and Schipper, B.A., "Developments in I-Sw measurements" Advances In Core Evaluation 2, Reservoir Appraisal, Gordon and Brech Science Publisher, Philadelphia 1991, p257
3. Wilson, O.B. and Skjæveland S.M. (2002),"Porous Plate Influence On Effective Imbibition Rates In Capillary Pressure Experiments" SCA 2002 – Monterey, USA.
4. Jerauld, G. R., and S. J. Salter, Effect of pore-structure on hysteresis in relative permeability and capillary pressure: Pore-level modeling, *Transport in Porous Media*, *5*, 103-151, 1990.
5. Shafer, J. and Lasswell, P., 2007, "Modeling Porous Plate Capillary Pressure Production Data: Shortening Test Duration and Quality Controlling Data", paper presented at the SPWLA 48th Annual Logging Symposium, held in Austin, Texas, June 3–6 June 2007.
6. Fleury M and Longeron DG (1997),"Full Imbibition Capillary Pressure Measurements On Preserved Samples Using The Membrane Technique", SCA 9716 – Calgary, Canada.
7. Lenormand, R, Delaplace, P, Schmitz, P., "Can we really measure the relative permeabilities using the micropore membrane method?" SCA-Paper 9637, presented at the SCA Symposium in Montpellier, 1996
8. Hammervold, W.L. and Skjæveland S.M., "Improvement of Diaphragm Method for Drainage Capillary Pressure Measurement with Micro Pore Membrane" SCA 1992-05 Euro.

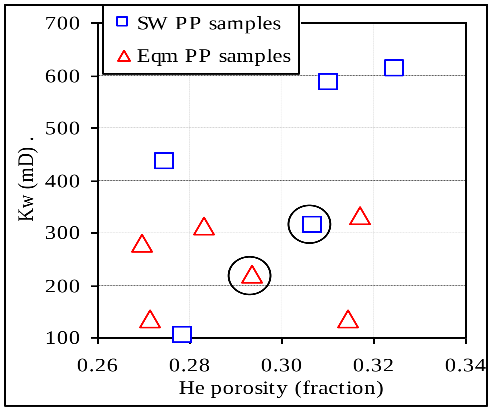

Figure 1 Kw versus porosity for all samples
Circles refer to plug #24 & #63

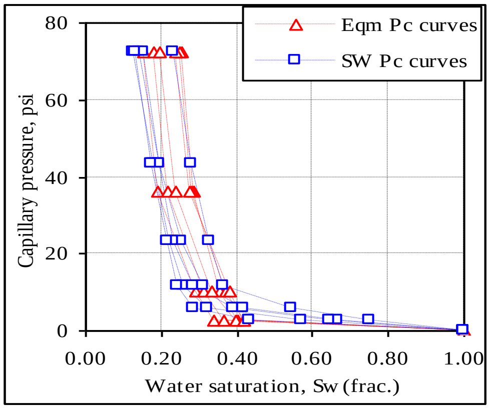

Figure 2 Pc-Sw for Eqm and short-wait PP

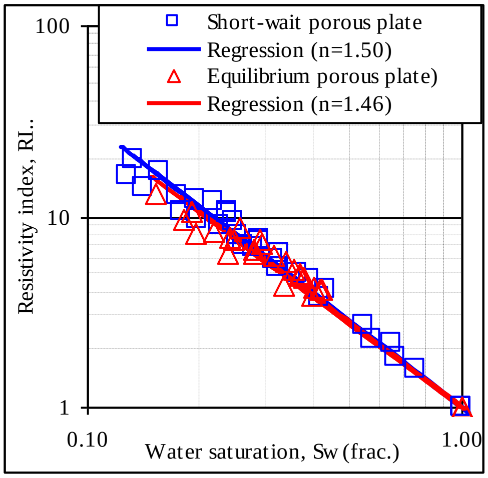

Figure 3 RI-Sw for Eqm and short-wait PP

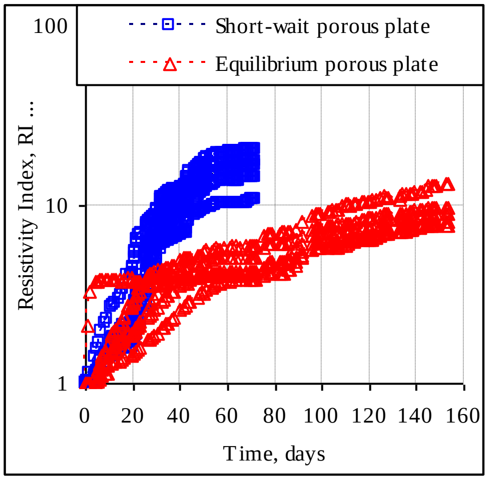

Figure 4 RI vs time for Eqm and short-wait PP

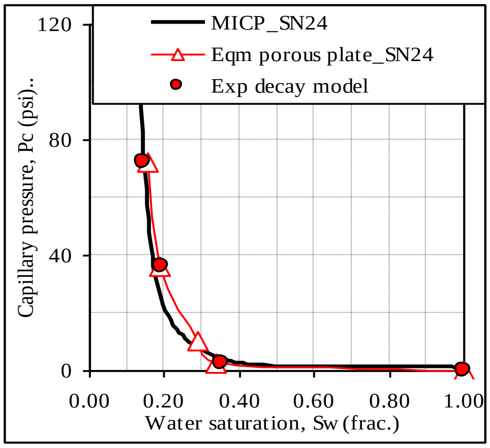

Figure 5 Model Pc with Eqm PP and MICP

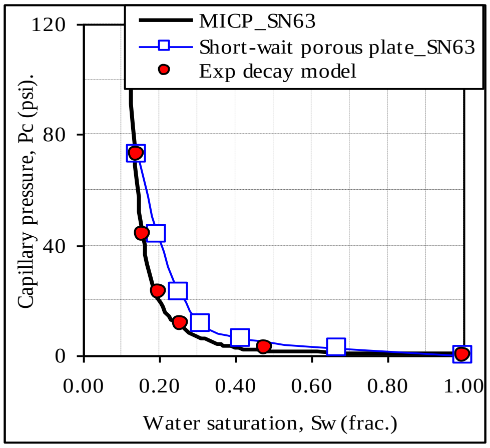

Figure 6 Model Pc with short-wait and MICP

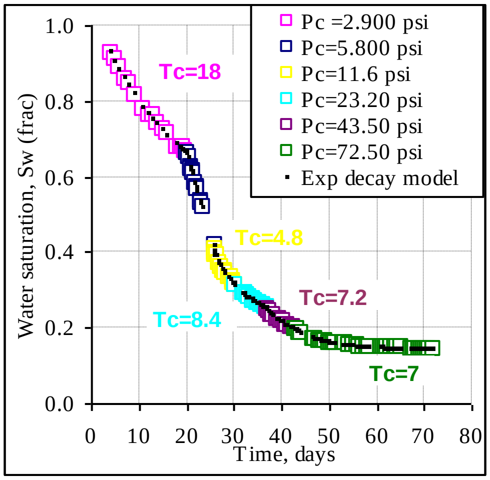

Figure 7 Model vs measured Sw_SN63

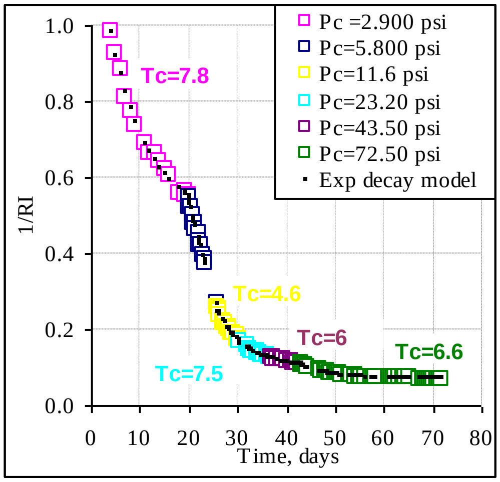

Figure 8 Model vs measured 1/RI_SN63