Capillary Pressure Curves Determined by Direct Measurement of the Saturation using Magnetic Resonance Imaging

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Abstract

Traditional techniques for measuring capillary pressure, such as porous plate, centrifugation, and mercury injection, are inaccurate and/or time-consuming. The centrifuge technique requires the fluid(s) to reach equilibrium at seven to ten different speeds. This is very time-consuming, as each equilibrium step can take up to two days or more. In addition, the inlet saturation must be computed using an approximate solution that is known to cause errors. Porous plate capillary pressure measurements are considered to be the most accurate, but acquiring the complete curve can take several months. Mercury injection is rapid but inaccurate as non-reservoir fluids are used, and the capillary pressure curve is modeled from the measurement pore throat sizes.

The new method described here, called GIT-CAP, centrifuges the core plugs, then directly measures the water saturation distribution inside the core plug using MRI. The measured water saturation together with the known centrifugal force, leads directly to a capillary pressure curve. The technique is rapid, requiring as few as a single equilibrium step, and is accurate, directly measuring the water saturation inside the rock. The technique is ideally suited to the study of "tight" or low permeability rocks. Tight rocks can easily take two to four days to reach equilibrium in a centrifuge or many weeks for porous plate, making the time savings achieved with GIT-CAP significant when compared to traditional measurement techniques.

Introduction

Capillary pressure, Pc, is the difference in pressure across the interface between two immiscible fluids and is dependent on the interfacial tension, pore size, and wetting angle. Capillary pressure is the most fundamental rock-fluid property in multiphase flows, just as porosity and permeability are for single phase flow in oil and gas reservoirs (Lake 1989). Capillary pressure curves directly determine the irreducible water saturation, residual oil saturation, rock wettability, and can be used to determine water-oil or water-gas contact points and approximate oil or gas recovery. Water flood performance is also significantly affected by the capillary pressure of the rock (Masalmeh 2003).

Capillary pressure is typically measured in the laboratory by using mercury injection, porous plate, or centrifugation techniques (Dullien 1991). The porous plate method is considered the most direct and accurate method but takes a long time since each capillary pressure point requires an equilibrium time that can take weeks or months. The mercury injection method is fast and can reach very high capillary pressures but the test uses a non-representative fluid, mercury, and it is destructive. In addition, mercury injection is an indirect measurement as it measures pore throat sizes which are then interpreted into capillary pressure. A common compromise between porous plate and mercury injection is centrifugation (Hassler and Brunner 1945). This method uses reservoir fluids and decreases the equilibrium time by using high centrifugal forces.

This paper describes a new method (Green et al 2007, US Patent 7,352,179, Chen and Balcom 2005 and 2006) for measuring capillary pressure employing a centrifuge and a new quantitative magnetic resonance imaging (MRI) method for measuring fluid saturation. The capillary pressure is calculated from the Hassler and Brunner equation at each radial position in the rock. This together with saturation as measured by MRI at each position directly produces a capillary pressure curve with as few as a single centrifuge equilibrium.

Traditional Centrifuge Pc Measurement

Hassler and Brunner (1945) proposed a centrifuge method to determine capillary pressure saturation data from small core plugs. In this method, a fluid saturated core plug, confined in a special core-holder, is rotated at different rotational speeds as shown in Figure 1. In the Figure, the relevant distances, de-

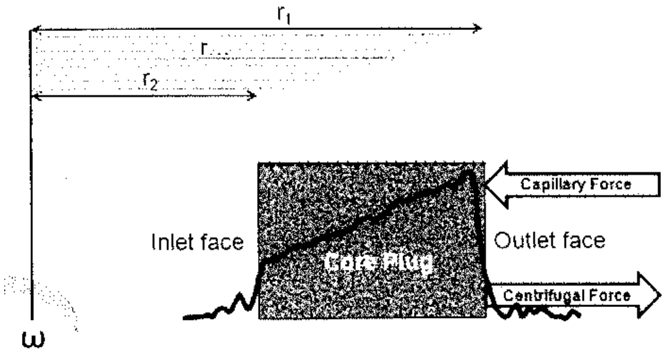

Figure 1 - Schematic of a rock core plug spinning in a centrifuge with a typically saturation profile overlaid

noted as r_1, r_2 and r, are the distances from the rotational axis to the inlet face, the outlet face, and any point along the core length, respectively. The core-holder contains another fluid which replaces the fluid displaced from the core. After reaching hydrostatic equilibrium, the amount of liquid expelled from the core plug is measured. From the expelled water the average water saturation at each centrifuge speed is known, and using an approximate solution, the saturation at the inlet face can be obtained. This saturation is plotted against the capillary pressure at the inlet as calculated from the centrifuge speed. This procedure is repeated 7-10 times to fully define the capillary pressure curve.

When a cylindrical core is placed in a centrifuge, a centrifugal acceleration $a_c = -\omega^2 r$, is generated, where w is the angular rotation speed of the centrifuge and r is the distance from the axis of rotation. Applying Darcy's law at hydrostatic equilibrium and using the Hassler-Brunner boundary condition that the outlet capillary pressure is zero (i.e. 100% saturation), we have

$$P_c(r) = \frac{1}{2}\Delta\rho\omega^2(r_2^2 - r^2)$$

where Δr is the density difference between wetting fluid and non-wetting fluid.

The radial capillary pressure distribution results in a fluid saturation distribution along the length of the core. Neither of these distributions is actually measured with the traditional method. What is measured is the rotational speed, ω, and the average fluid saturation, $\bar{S}$, within the core. The average fluid saturation of the core after centrifugation can be expressed as

$$\bar{S} = \frac{1}{r_2 - r_1}\int_{r_1}^{r_2} S(r)dr$$

Equation (2) may be rewritten and mathematically manipulated to yield the Hassler-Brunner integral equation

$$\bar{S}P_{cL} = \frac{r_1 + r_2}{2r_2}\int_0^{P_{cL}} \frac{S(P_c)}{\sqrt{1 - \frac{P_c}{P_{cL}}(1 - \frac{r_1}{r_2})}} dP_c$$

Equation (3), however, cannot be directly solved for the unknown function S. A number of approximate solutions exist to obtain the required inlet saturation (Ruth and Chen 1995, Forbes 1997, Rajan 1986). Hassler and Brunner assume short cores (i.e. $r_1/r_2 \approx 1$), and in differential form equation (3) is reduced to

$$S_L = \frac{d(\bar{S}P_{cL})}{dP_{cL}}$$

The inlet Pc is calculated at each rotational speed by setting r to r_1 in equation (1) and, saturation at the inlet face, S_L, is obtained according to equation (4). A plot of these two values, inlet Pc and inlet saturation, at different rotation speeds yields the capillary pressure curve.

Magnetic Resonance Imaging

Nuclear Magnetic Resonance (NMR) detects the amount of hydrogen (for proton NMR) in the sample or object under study. The lifetime of the detected NMR signal depends on the environment of the hydrogen. For example, signal detected from the hydrogen in most oils decays away faster than the hydrogen in free water. Magnetic resonance imaging (MRI) spatially resolves the NMR signal. Spatially resolving the MRI signal is achieved by linearly altering the magnetic field creating a magnetic field gradient. Both the field of view and the resolution are limited by the linear region and strength of the magnetic field gradient. A wide variety of different pulse sequences (combinations of gradient, excitation, and detection schemes) are available. The main difficulty with NMR (or MRI) is that because the signals are dependent upon so many things (amount of hydrogen, pore size, fluid diffusion, etc), obtaining quantitative results can be difficult.

The standard SPRITE MRI (Balcom et al. 1996) technique has proven, over the last 10 years, to be a very robust and flexible method for the study of a wide range of systems with short magnetic resonance relaxation times. As a pure phase encoding technique, SPRITE is largely immune to image distortions due to susceptibility variation, chemical shift, and paramagnetic impurities. Repetitive excitation and data acquisition are performed in the presence of ramped phase encoding gradients, which enable systems with short signal lifetimes to be successfully visualized.

A centric scan strategy for SPRITE MRI (Mastikhin 1999) removes the longitudinal steady state from the image intensity equation of standard SPRITE imaging, increases the inherent image intensity, and makes the detected signal only depend on the amount of hydrogen. The image signal intensity no longer depends on the spin-lattice relaxation time (T_1) and the repetition time making centric scan SPRITE an ideal method for quantitative imaging of sedimentary rocks with short relaxation times (Chen, Halse and Balcom 2005). A 1D double half k-space SPRITE (DHK) technique, also called 1D centric scan SPRITE, is illustrated in Figure 2.

Capillary Pressure Curves

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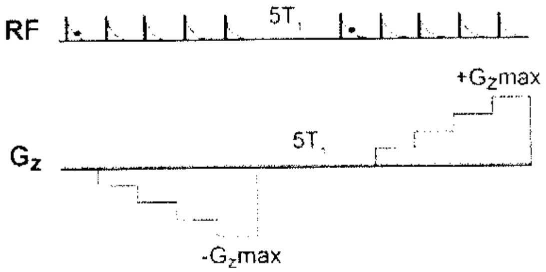

Figure 2 - The double half k-space version of the SPRITE MRI method

Other MRI methods have a T_2 dependence which is known to be multi-exponential and depend heavily on the saturation level. This makes quantitative analysis nearly impossible with these MRI methods (Baldwin and Spinler 1998).

MRI-based Capillary Pressure

Capillary pressure theory combined with MRI-determined saturation profiles allow us to directly obtain capillary pressure curves. With this technique, the centrifuge is used to create a distribution of fluid in the rock core plug dependent on capillary pressure, which then can be quantified using MRI. The capillary pressure at each position down the rock at hydrodynamic equilibrium is known from equation (1). The saturation at the corresponding positions is measured using MRI. The fully saturated profile gives us the 100% saturation level. We know that the 0% saturation level will yield no MRI signal as there is no hydrogen present. Therefore, dividing the centrifuged measured profile by the 100% saturated profile gives a quantitative saturation level versus position. Figure 3 shows a fully saturated and a series of centrifuged profiles.

The radial distance is determined at each profile point knowing that one edge is the distance r_2, see Figure 1. The capillary pressure is then computed using equation (1) at each point and plotted with the saturation percent to create a capillary pressure curve.

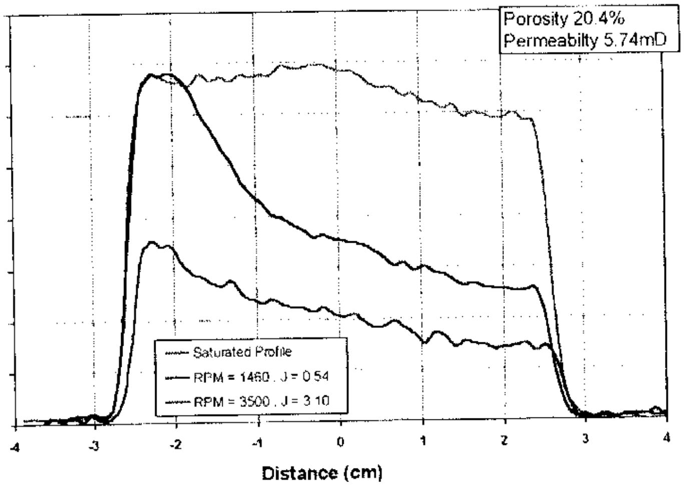

Figure 3 - MRI profiles of 1.5" diameter rock core plug. The fully saturated profile is the relatively uniform profile showing the homogeneity of the rock. The remaining profiles are acquired after successively higher centrifuge speeds. The left edge is the outlet face.

Saturation profiles acquired after centrifugation at different speeds are plotted on the same curve expanding the range and resolution of the capillary pressure curve. The rotational speed(s) can be estimated by using the Leverett J function (Leverett 1941)

$$P_c(r) = \frac{1}{2}\Delta\rho\,\omega^2\left(r_2^2 - r_1^2\right) \geq \frac{J(S_{wi})\sigma\cos\theta}{\sqrt{\frac{k}{\phi}}}$$

where J is the Leverett value, is the normal interfacial tension, is the contact angle, k is the permeability and is the porosity for a given rock. The J value "normalizes" the speed using this function (Brown 1951).

Results and Discussion

The new MRI-based method has proven to correlate very well with existing centrifuge and porous plate measurements (Green et al. 2007, 2008). This MRI-based capillary pressure measurement technique directly measures the water saturation in the rock core plug. Traditional centrifuge techniques measure the

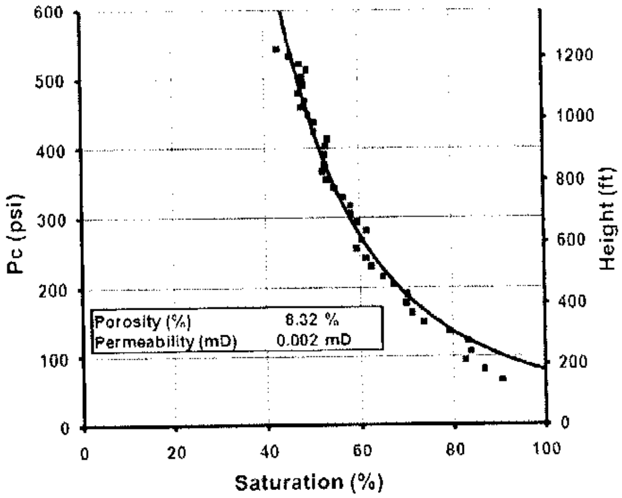

Figure 4 - Air/brine capillary pressure curve of a low permeability rock

expelled water and require simplifications and assumptions. The capillary pressure measurement using MRI requires only that the outlet boundary condition be met (i.e. 100% saturation at the outlet face). The assumption that the core plug length is negligible compared to the radius of rotation is not required in this new technique. In fact, the measurement relies on the capillary pressure gradient and the subsequent saturation gradient along the length of the core plug.

A typical air/brine result for a very low permeability core is shown in Figure 4. In this example, a single centrifuge equilibrium was used to acquire the Pc curve. The total experiment time was two days for core preparation, four days for the one centrifuge step, and less than two hours for the NMR scanning. A traditionally acquired Pc curve with only ten data points would have taken approximately 42 days. An additional benefit of the technique is that the T_2 pore size distribution can be acquired with virtually no increase to the overall experiment duration. The corresponding T_2 measurements; one fully saturated showing the pore size distribution, and the second used to determine connate water saturation, bound volume, and T_2 cut-off are shown in Figure 5.

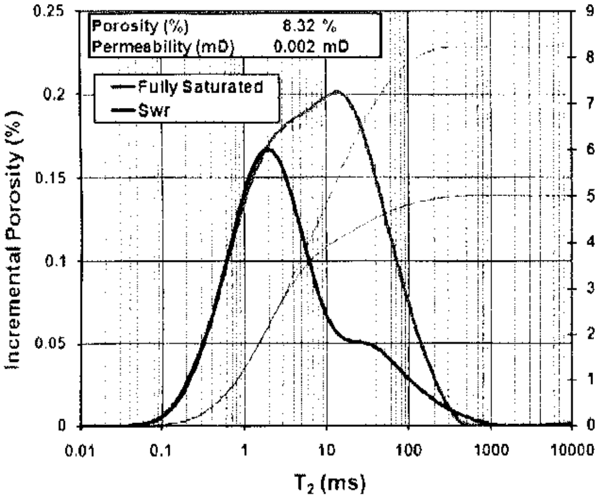

Figure 5 - T_2 cutoff measurements of a low permeability rock

The technique is easily expanded to oil/brine studies by using deuterium oxide for the brine. This makes the brine phase invisible to the NMR and only the oil phase is detected. A simple subtraction from the fully saturated profile yields the water phase. A typical oil/brine result is shown in Figure 7. In this example, the full set of capillary pressure curves was obtained; primary drainage, imbibition, and secondary drainage. The total experiment time for this measurement was 7 days compared to more than 60 days for the traditionally acquired measurements.

The GIT-CAP technique requires the rock core plug to be moved from the centrifuge to the MRI scanner which takes time. Much care and investigation has been given to the question of the redistribution of fluids between these two steps. It was found that there were two mechanisms that can cause changes in the fluid distribution in a rock: 1) spontaneous imbibition of "free" fluid into the rock; and 2) redistribution of fluid within the rock. Spontaneous imbibition of fluid can occur very rapidly (< 1 minute) but as long as free fluid does not come into contact with the rock this process cannot occur. This is easily achieved by using the standard receiving tubes used in traditional centrifuge capillary pressure measurements.

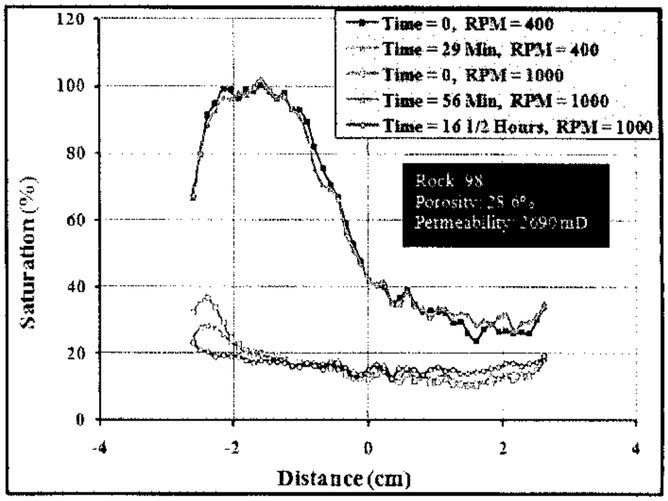

Figure 6 - Redistribution of fluid following centrifugation

Fluid redistribution within the rock is minimized by acquiring the MRI profiles directly after centrifugation. The MRI measurement time is typically between a few minutes and a couple of hours with the longer measurement times required for rocks that are desaturated and therefore have less fluid distributed within the rock after centrifugation. The redistribution of fluids is insignificant in the time required to acquire the MRI profile. Figure 6 shows the MRI saturation distribution down the rock length acquired after centrifugation repeated at different time intervals. In this case, the fluid still has not fully redistributed after two days. Even the high permeability (>2,500mD) rocks take at least 1 hour for any noticeable redistribution to occur within the rock.

Although it would be ideal to acquire the complete capillary pressure curve at one centrifuge speed, operational and MRI resolution restrictions may prevent this. In order to acquire a complete capillary pressure curve, the centrifuge speed must be selected such that the connate water saturation is achieved at the inlet face of the rock. This can be estimated but cannot be

Capillary Pressure Curves

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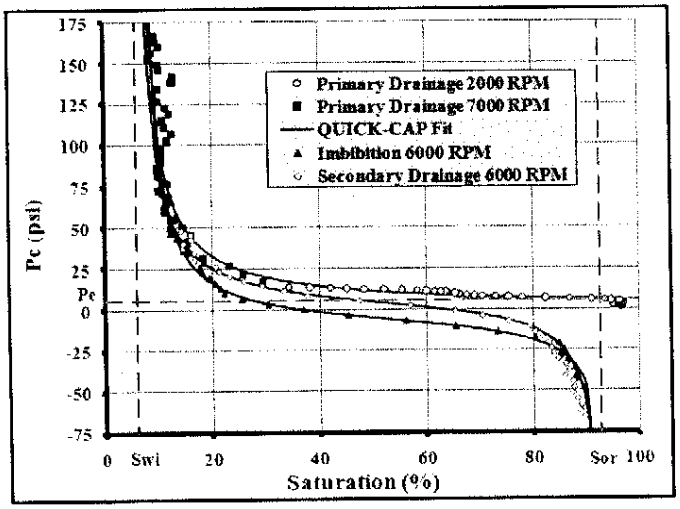

Figure 7 - Oil/brine capillary pressure curves

assured for all rocks. Study has also shown that it is difficult, at the lower capillary pressures, to fully define the curve. It also appears that the 100% saturation at the outlet face may be a very thin layer which cannot be resolved at the MRI resolutions currently used. In the end, it seems apparent that at least two centrifuge speeds will be required. The best two centrifuge speeds appear to be achieved when J=0.5 and J=4. The J=0.5 centrifuge speed allows the capillary entry pressure to be accurately determined. These values can be changed if different portions of the Pc curve are desired (i.e. higher pressures).

A number of additional benefits can be exploited using this technique. The fully saturated profiles can indicate inhomogeneities in the rocks and can be used to determine the pore volume. If the homogeneities are only in a portion of the rock, capillary pressure curves can still be obtained by only using the homogeneous section or alternatively an optimistic and pessimistic Pc curve can be generated from the same data. Another benefit is the ability to use longer rock core plugs to increase the maximum capillary pressure (i.e. decrease r in equation (1)). Longer core plugs will not only increase the maximum capillary pressures, but it will also increases the absolute water volume which will increase the NMR signal to noise ratio decreasing the scanning times. Another benefit is a simpler centrifuge setup. The centrifuge used in this type of measurement need not measure the expelled fluid as we directly measure the water in the rock. This greatly simplifies the centrifuge design and, in turn, significantly reduces the cost both in terms of capital costs, and ongoing maintenance requirements.

Conclusions

The new MRI-based capillary pressure measurement technique (GIT-CAP) is an excellent method to measure capillary pressure. In particular, it is beneficial for low permeability rocks as these rocks require high centrifuge speeds and long equilibrium times. The technique requires far fewer centrifuge equilibrium steps (typically two) and thus decreases the measurement time for a capillary pressure curve by a factor of three to five times. In addition, this measurement is inherently more accurate because the water saturation is directly measured in the rock. Also, GIT-CAP does not necessitate expensive centrifuge modifications and T_2 NMR data can be acquired during the test protocol with little or no time penalty.

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