A SINGLE-SHOT METHOD FOR DETERMINING DRAINAGE AND IMBIBITION CAPILLARY PRESSURE CURVES

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This paper was prepared for presentation at the International Symposium of the Society of Core Analysts held in Trondheim, Norway 12-16 September, 2006

ABSTRACT

A single-shot method to determine the capillary pressure curve employed a single rotational velocity centrifugation experiment and one-dimensional Centric Scan SPRITE (single-point ramped imaging with T_1 enhancement) MRI (magnetic resonance imaging) to determine the fluid saturation distribution, S(r), along the length (r) of the core. A full capillary pressure curve can be directly determined by the relation of S(r) and the capillary pressure distribution, $P_c(r)$. The rotational speed required for the single-shot method can be determined with the Leverett J function value at the irreducible water saturation. Centric scan SPRITE MRI is an ideal method for measuring spatially resolved fluid saturation in rocks. The single-shot method has been applied to measure the primary drainage, as well as imbibition and secondary drainage capillary pressure curves for reservoir rocks. Proper boundary conditions are ensured by maintaining the free water level in contact with the outlet face of the core. Deuterium oxide (D_2O) instead of H_2O was employed to dissolve salt for preparing synthetic brine to determine fluid saturation with MRI unambiguously. Thus crude oil can be applied for centrifuging at reservoir temperature with the single-shot method.

The single-shot method for determining the capillary pressure curve is rapid, cheap, accurate and adaptable. The capillary pressure curve can be obtained straightforwardly with approximately 40 data points. A desktop centrifuge and a desktop permanent magnet based one-dimensional MRI instrument can be employed for the single-shot method. After primary drainage and imbibition measurements, the rock core should be managed to reach a uniform irreducible water saturation distribution and uniform residual oil saturation distribution, respectively. MRI was also employed to check the saturation distribution. Since only a single rotational velocity is employed, there is no pressure effect on rock pore structure due to dramatic rotational speed changes required for traditional methods. The effect of gravity can also be neglected. In addition, the long rock cores preferred for the single-shot method result in a relatively small radial effect and reduced rotational speed; friable and unconsolidated samples may be measured.

In addition, application of the single-shot method for a disk-shaped rock sample and the design of non-magnetic centrifuge disk-shaped rock sample holder will also be presented.

For the spinning disk approach, there is no radial effect and large diameter cores are preferred.

INTRODUCTION

In the laboratory, the capillary pressure curve can be determined with (1) mercury injection, (2) porous plate, and (3) centrifugal methods, based on hydrostatic equilibrium [Dullien (1991)]. The porous plate method is a direct and accurate technique, but the measurement is extremely time-consuming, since the equilibration time can be weeks or months for each individual pressure point. The mercury injection method is rapid, but it is a destructive method. In addition, the mercury injection measurement does not provide information on reservoir wettability, and mercury is hazardous to human health and the environment.

The centrifuge method was first introduced by Hassler and Brunner (1945). This method involves rotating fluid bearing rock cores at variable rotational speeds in a specially modified centrifuge. The rotation of the sample yields a centrifugal force which will counterbalance the capillary pressure when hydrostatic equilibrium is reached. Collecting and measuring the expelled fluid after hydrostatic equilibrium is achieved, as a function of the rotational speeds, permits a quantification of the capillary pressure as a function of fluid saturation [Ruth and Chen (1995), Melrose (1986), Rajan (1986)]. A full capillary pressure curve determined with traditional centrifugal methods requires approximately 10 different centrifuge speeds, thus the measurement for a capillary pressure curve takes several days to more than a week depending on equilibrium time. In addition, the experiment requires a very expensive ultracentrifuge with precise speed control over a wide range of speeds. This technique has been extensively investigated, and is commonly used in the petroleum industry.

In the current investigation, we continue the development of a new "single-shot" method to measure the capillary pressure curve using a single-speed centrifuge experiment and one dimensional quantitative magnetic resonance imaging (MRI) to determine the fluid saturation distribution, S(r), along the length of the sample, instead of non-quantitative spin echo based MRI [Baldwin and Spinler (1998)], and nuclear tracer imaging techniques [Graue et al. (2002)]. A full capillary pressure curve can be determined by the relationship between S(r) and the capillary pressure distribution, $P_c(r)$, along the length of the core [Chen and Balcom (2005)].

TRADITIONAL CENTRIFUGE METHODS

In 1945, Hassler and Brunner proposed a centrifuge method to determine capillary pressure-saturation data from small core plugs. They also proposed an approximate solution to the basic equation relating capillary pressure and average saturation by neglecting the gravity effect and assuming the length of the core was negligible compared to the radius of rotation.

In a centrifuge capillary pressure experiment, a fluid saturated core plug, confined in a special core-holder, is rotated at different rotational speeds. The relevant distances are denoted as r_1, r, and r_2, 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 with a stroboscope [Rajan (1986)].

The basic concepts for capillary pressure measurement with a centrifuge are outlined below.

When a cylindrical core is placed in a centrifuge, a centrifugal acceleration $a_c = -\omega^2 r$, is generated, where ω 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, we have

$$\frac{dP_c}{dr} + \Delta\rho\omega^2 r = 0 \qquad (1)$$

where $\Delta\rho$ is the density difference between wetting fluid and non-wetting fluid.
The differential equation can be solved by simple integration and application of the Hassler-Brunner boundary condition, i.e., $P_{c2} = 0$, so

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

the capillary pressure at the inner face of the core is given by

$$P_{cL}(r) = P_c(r_1) = \frac{1}{2}\Delta\rho\omega^2(r_2^2 - r_1^2) \qquad (3)$$

The 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, $\overline{s}$, within the core.

The average fluid saturation of the core after centrifugation can be expressed as

$$\overline{S} = \frac{1}{r_2 - r_1}\int_{r_1}^{r_2} S(r)dr \qquad (4)$$

Equation (4) may be rewritten by changing the integration variable $P_c(r_2)=0$ and $P_c(r_1)=P_{cL}$, with additional mathematical manipulation, which yields the Hassler-Brunner integral equation

$$\overline{S}P_{cL} = \frac{r_1 + r_2}{2r_2}\int_0^{P_{cL}} \frac{S(P_c)}{\sqrt{1 - \frac{P_c}{P_{cL}}(1 - \frac{r_1^2}{r_2^2})}} dP_c \qquad (5)$$

Based on equation (5), a number of other approximate solutions have been developed and used to determine capillary pressure curves [3, 9].

SPRITE MRI

Standard SPRITE MRI

The standard SPRITE MRI [Balcom et al. (2003, 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 MR 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 T_2^* lifetimes as short as tens of microseconds to be successfully visualized.

Centric scan SPRITE MRI

A centric scan strategy for SPRITE MRI [Mastikhin (1999)] removes the longitudinal steady state from the image intensity equation of standard SPRITE imaging, and increases the inherent image intensity. The image signal intensity no longer depends on the spin-lattice relaxation time (T_1) and the repetition time. These features ensure that centric scan SPRITE is an ideal method for quantitative imaging of sedimentary rocks with short relaxation times.

A 1D centric scan SPRITE technique is illustrated in figure 1, where the k-space data are acquired sequentially from '0' to '-k_z', corresponding to a gradient change from 0 to minus maximum gradient (-Gmax), after a delay of 5 times T_1, the other of half k-space data is collecting from '0' to '+k_z', corresponding to a gradient change from 0 to a maximum gradient (Gmax). Fourier transformation of the k-space data yields a real space image. In the centric scan SPRITE method, the image signal intensity (S) is given by:

$$S(r) = M_0(r)\exp(-\frac{t_p}{T_2^*})\sin\alpha \qquad (6)$$

where M_0 is the equilibrium magnetization, α is the RF flip angle, t_p is the phase encoding time, T_2^* is the effective spin-spin relaxation time. M_o is directly proportional to the local fluid content. Centric scan SPRITE methods are naturally fluid content weighted.

Quantitative Imaging with SPRITE MRI

A wide range of experimental results [Chen et al. (2005)] show that the overall FID (free induction decay) decay rate ($1/T_2^*$) in fluid saturated sedimentary rocks is dominated by an internal field distribution (ΔB^i) induced by the large susceptibility difference ($\Delta\chi$) between the pore filling fluid and solid matrix due to paramagnetic impurities in the solid matrix. The decay rate of the FID and the corresponding MR linewidth ($\Delta\nu=1/\pi T_2^*$) for fluid saturated sedimentary rocks may be estimated by [Chen et al. (2005)],

$$\frac{1}{\pi T_2^*} = \Delta\nu \approx \frac{\gamma\Delta B^i}{2\pi} = \frac{C\Delta\chi\gamma B_0}{2\pi} \qquad (7)$$

where γ is the gyromagnetic ratio, and B_0 is the applied magnetic field strength, while C is a dimensionless constant.

Equation (7) predicts a single exponential T_2* decay, this prediction has been confirmed by a wide range of MR experiments for sedimentary rocks [Chen et al. (2005)]. Single exponential T_2* decay is anticipated for a wide variety of sedimentary rock systems, but is not a universal result. Equation (7) also predicts that effective transverse relaxation time (T_2*) is inversely proportional to the applied magnetic field strength (B_0). It suggests that low field MR will lead to a longer MR signal lifetime.

Figure 2 shows a semi-logarithmical FID decay after a 90 degree RF excitation pulse. The data was fit to the equation:

$$S = M_0 \exp(-t/T_2^*) \qquad (8)$$

where S is the MR signal intensity, t is the acquisition time. The fit T_2^* was 345 μs. We have observed for many sedimentary rocks that T_2* is largely insensitive to water saturation with a single exponential FID. These features ensure that Centric Scan SPRITE methods permit quantitative imaging. Quantitative images are frequently impossible with spin echo based MRI methods, due to multi-exponential T_2 decay in porous rocks [Baldwin and Spinler (1998)].

SINGLE-SHOT METHOD - DRAINAGE AND IMBIBITION CAPILLARY PRESSURE CURVES

Experimental procedures

In the single-shot measurement of capillary pressure curves of water and oil, it is necessary to distinguish between oil and water phases by MRI. This may be undertaken by employing D_2O instead of H_2O to dissolve salt for preparing synthetic brine to make the water phase invisible to ^1H MRI, using crude oil, and centrifuging at reservoir temperature.

Experimental procedures for primary drainage, imbibition, and secondary drainage capillary pressure curves follow:

1. The cylindrical core sample was dried at 80°C until a constant weight was reached, and the weight of the dried sample was determined.
2. The core sample was kept under vacuum conditions for more than 24 hours, and then saturated with distilled water (H_2O) under vacuum conditions until no bubbles came from the core, and the weight of the saturated sample was determined.
3. A proton (^1H) one-dimensional Centric Scan SPRITE MRI measurement was carried out on the sample which was wrapped with Teflon tape to decrease the evaporation of liquid within the core sample during MRI measurements. A water distribution along the length of the sample was obtained and normalized by the total volume of water in the core sample.
4. Steps 1 to 2 were repeated, D_2O instead of H_2O was employed to saturate the core sample.
5. The core sample was put into an oil and D_2O filled sample tube, with free water level contact with outlet face of the core, for centrifugation at 3000 rpm in a centrifuge for 24 hours for primary drainage capillary pressure curve measurement.

6. The core sample was taken from centrifuge, and its weight determined.
7. A proton (^1H) 1D Centric scan SPRITE MRI measurement was carried out on the sample which was wrapped with Teflon tape to decrease the evaporation liquid within the core sample during MRI measurements. The oil distribution along the length of the sample was obtained and normalized by the total volume of oil in the sample. The D_2O distribution along the length of the sample was obtained by subtracting the volume normalized oil distribution from the volume normalized water distribution along the length of the core sample. The water saturation (S_w) distribution along the length of the core sample after centrifugation was determined from the volume normalized D_2O distribution after centrifugation divided by the volume normalized H_2O distribution before centrifugation. The capillary pressure curve was determined with saturation distribution and capillary pressure distributions along the length of the core sample.
8. The core sample was flipped and spun in the centrifuge, then flipped and spun again several times to reach a relatively uniform irreducible water saturation (S_{wi}) distribution along the length of the core sample to prepare the core sample for imbibition capillary pressure curve measurement.
9. The core sample was put into a D_2O and oil filled sample tube, with the free water level in contact with the outlet face of the core, for centrifugation at 3000 rpm in centrifuge for 48 hours for imbibition capillary pressure curve measurement.
10. Steps 6 to 7 were repeated.
11. The core sample was flipped and spun in the centrifuge, then flipped and spun again several times to reach a relative uniform residual oil saturation (S_{or}) distribution along the length of the core sample to prepare the core sample for secondary drainage capillary pressure curve measurement.
12. The core sample was put into an oil and D_2O filled sample tube, with the free water level in contact with the outlet face of the core, for centrifugation at 3000 rpm in the centrifuge for 48 hours for the secondary drainage capillary pressure curve measurement.
13. Steps 6 to 7 were repeated again.

Experimental results

A cylindrical sandstone sample, with a porosity of 0.28, and a permeability of 370 md, was employed for the measurements. The dimensions of the core were measured to determine the bulk volume of the rock sample. The capillary pressure measurements were conducted according to the experimental procedures in the previous section.

The centrifuge experiment was carried out with a Z513K tabletop centrifuge (Hermle Labortechnik, Germany) with arm length of 23.5 cm, at 3000 RPM for 24 or 48 hours.

The MRI experiments were carried out in a 0.2 Tesla permanent magnet with an Apollo console (Tecmag Inc., Houston, TX). A 3 cm inner diameter solenoid probe was employed. The core sample was wrapped with Teflon tape to decrease the evaporation of liquid within the samples during MRI measurements. The advantages of using a low-field

MRI instrument are that (1) the instrument is cheap, and (2) the effective spin-spin relaxation time (T_2*) is much longer than the phase encoding time (t_p). This ensures the SPRITE MRI image is a simple fluid distribution image.

In the experiments, decane was employed as the oil phase. Crude oil can also be used in the experiment to simulate reservoir conditions at reservoir temperature. The fluid content profiles along the length of the core before and after centrifugation, were determined by one-dimensional centric scan SPRITE MRI with a phase encoding time of 50 μs, flip angle α of 6 degrees, with an image matrix size of 64 points. 16 signal averages were acquired for a total acquisition time of one minute. More data points along the length of the core can easily be obtained by increasing the image matrix size and/or decreasing the field of view of the image. This results in more data points on the capillary pressure curve.

Figures 3, 4 and 5 show the 1D water saturation distribution along the length of the core after primary drainage, imbibition, and secondary drainage, respectively. Therefore, the relationship between capillary pressure and the corresponding water saturation can be determined very straightforwardly. The primary drainage, imbibition, and secondary drainage capillary pressure curves are shown in Figure 6. The curves of Figure 6 are physically sensible and closely approximate similar curves in the literature [Donaldson et al. (1969)]. However, the difficulty of conventional centrifuge measurement methods means such curves are rarely determined in practice. The current methodology shows they may now be determined with some ease.

Discussion

The single-shot method for determining the capillary pressure curve is rapid, cheap, accurate and adaptable. The rotational speed for the single-shot measurement may be determined by the Leverett J function [Leverett (1941)] with a J value of 4 at the irreducible water saturation [Brown (1951)]. The capillary pressure curve can be obtained straightforwardly with approximately 40 data points. A typical traditional centrifuge for the capillary pressure measurement employs 10 rotational speeds with 4 or 6 samples running simultaneously, however, the new centrifuge method requires only a single rotational speed with a maximum of 30 samples running simultaneously. The overall duration of the experiment for the single-shot method is thus more than 50 times reduced from the traditional centrifuge method. In other words, we believe that the one single-shot system will have a theoretical sample throughput equivalent to 50 ultracentrifuge systems. A cheap desktop centrifuge and a relatively inexpensive desktop permanent magnet based one-dimensional MRI instrument can be employed for the single-shot method, instead of the very expensive traditional ultracentrifuge system.

In the single-shot method, the centrifugation experiment is just for sample preparation, the MRI is employed for the capillary pressure curve measurement. The MRI experiment for a fluid distribution measurement takes less than 1 minute. Therefore, two or more desktop centrifuges may work with one MRI instrument to increase the capacity dramatically without significant infrastructure cost increase. The overall duration of the new experiment may be even faster than mercury intrusion measurements for large quantities of samples.

After primary drainage and imbibition measurements for the traditional and new centrifuge methods, the rock core should be managed to reach a uniform irreducible water saturation distribution and uniform residual oil saturation distribution, respectively. MRI was also employed to check the saturation distribution.

For the single-shot method, since only a single rotational speed is employed, there is no pressure effect on the rock pore structure [Chen et al. (2002)] due to dramatic rotational speed changes required for the traditional method. The effect of gravity can also be neglected for the single-shot method. In addition, the long rock cores preferred for the single-shot method result in a relatively small radial effect [Christiansen and Cerise (1988)] and reduced rotational speed; some friable and unconsolidated samples may be applicable for the single-shot method, since extreme high rotational speeds are not necessary.

We did some experiments to measure fluid redistribution after centrifugation. We have observed that it takes about one hour for water and air to redistribute after centrifugation. It takes much longer time for water and oil to redistribute after centrifugation. A typical one dimensional MRI scan time is 1 minute. Therefore, saturation re-distribution effect can be ignored during MRI scan after centrifugation. These experimental results will be elaborated in a future publication.

SINGLE-SHOT METHOD - SPINNING DISK-SHAPED ROCK

Experimental procedures

Experimental procedures for primary drainage capillary pressure curve of rock disk sample in rock disk centrifuge:

1. The rock disk sample was dried at 80°C until a constant weight was reached, and the weight of the dried sample was determined.
2. The rock disk sample was kept under vacuum conditions for more than 24 hours, and then saturated with distilled water (H_2O) under vacuum conditions until no bubbles came from the rock disk sample, and the weight of the saturated sample was determined.
3. A proton (H^1) Spiral SPRITE MRI measurement [Halse et al. (2003), Chen et al. (2005)] was carried out on the rock disk sample which was wrapped with Teflon tape to decrease the evaporation of water within the sample during MRI measurements. A water distribution along the radii of the sample was obtained and normalized with total volume of water in the rock disk sample.
4. The rock disk sample was put into an rock disk non-magnetic sample holder for centrifugation at 1920 rpm in a home-made spinning rock disk centrifuge for one hour for primary drainage capillary pressure curve measurement.
5. The step 3 was repeated.

6. The water saturation distribution along the radii of the rock disk sample after centrifugation was determined with the volume normalized water distribution after centrifugation divided by volume normalized water distribution before the centrifugation. The capillary pressure curve was determined with saturation distribution and capillary pressure distributions along the radii of the rock disk sample.

Experimental results and discussion

A Berea sandstone disk, 4 inches in diameter and half inch in thickness, was employed for the measurements. The capillary pressure measurements were conducted according to the experimental procedures in the previous section.

The centrifugation experiment was carried out with a home-made spinning rock disk non-magnetic sample holder and centrifuge (figures 7 and 8), at 1920 RPM for one hour, the temperature in the centrifuge was controlled to be 4°C to avoid water evaporation of water within the rock disk sample during the centrifuge experiment.

SPRITE MRI experiments were carried out in a 2.4 Tesla horizontal bore superconducting magnet (Nalorac Cryogenics Inc., Martinez, CA) with an Apollo console (Tecmag Inc., Houston, TX). A 14 cm inner diameter eight-rung quadrature birdcage probe (Morris Instruments, Ottawa, ON) was employed. The core samples were wrapped with Teflon tape to decrease the evaporation of water within the samples during MRI measurements.

The two-dimensional images before and after centrifugation, were obtained by Spiral-SPRITE MRI with a phase encoding time of 50 μs, flip angle α of 6 degrees, for a field of view of 17 cm, with an image matrix size of 64*64 points. 64 signal averages were acquired for a total acquisition time of 3 minutes. More data points along the length of the core can easily be obtained by increasing the image matrix size and/or decreasing the field of view of image, which results in more data points on the capillary pressure curve. Figures 9 and 10 show the two-dimensional images of the rock disk sample before and after centrifugation, respectively. The images display a bedding structure. After centrifugation, the average water saturation was 44%. A radial average image processing approach is applied to simplify the determination of water saturation distribution and to increase the signal to noise ratio of the image. This approach averages pixels along the circumference of circles with variable radii. Therefore, the larger of the radii, the more data points of image are available for averaging. Figure 11 shows the water saturation distribution along the radii (r) of the rock disk. Therefore, the relationship between capillary pressure and the corresponding water saturation can be determined very straightforwardly. The capillary pressure curve is shown in Figure 12.

For the spinning disk approach [Al-Modhi and Christiansen (1998)], there is no radial effect and large diameter cores are preferred. But this approach lacks the multiple samples advantage, and the disk-shaped sample does not fit a commercial centrifuge. In addition, two-dimensional imaging is required for the spinning disk approach.

CONCLUSIONS

The single-shot method combines a single-speed centrifuge experiment and a quantitative SPRITE MRI technique to directly determine the fluid saturation distribution along the length of the core. The proposed method for determining capillary pressure curve is rapid, cheap, accurate and adaptable. The capillary pressure curve can be obtained straightforwardly with approximately 40 spatial image data points. The duration of the experiment is much less than the traditional centrifuge method. For the single-shot measurement, the outlet boundary condition can be maintained by free water level, the effect of gravity can be neglected, and there is no effect of centrifuge speed variations on pore structure of rocks. In addition, a long rock core preferred for the single-shot method result in a relatively small radial effect compared with a short sample; some friable and unconsolidated samples may be applicable for the single-shot method. The single-shot method has been applied to measure the primary drainage, imbibition, and secondary drainage capillary pressure curves for reservoir rocks.

The single-shot method should make it possible for the capillary pressure curve measurement to become a ‘routine’ rather than a ‘special’ core analysis measurement.

ACKNOWLEDGEMENTS

BJB thanks NSERC of Canada for discovery and equipment grants. BJB also thanks the Canada Chairs program for a Research Chair in MRI of Materials (2002-2009). The UNB MRI Centre is supported by an NSERC Major Facilities Access grant. The authors thank the Idea to Innovation program of NSERC for funding support and R.P. MacGregor for his technical assistance.

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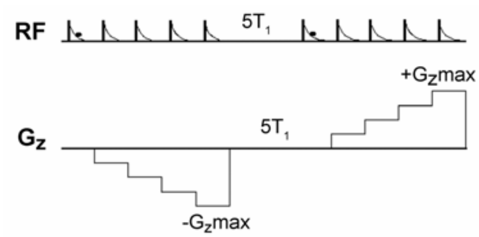

Figure 1. 1D centric scan SPRITE MRI pulse sequence.

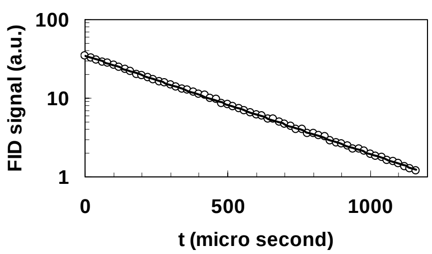

Figure 2. A semi-logarithmical plot of the MR FID (free induction decay) of the water saturated sandstone. The best fit line is single exponential with a decay time constant T_2^* of 345μs.

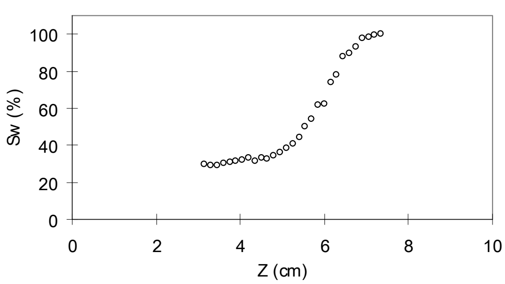

Figure 3. Water saturation distribution along the length (Z) of core #126 after centrifugation at 3000 rpm in oil for 24 hours for primary drainage capillary pressure measurement. The water saturation is 100% at the outlet face of the core.

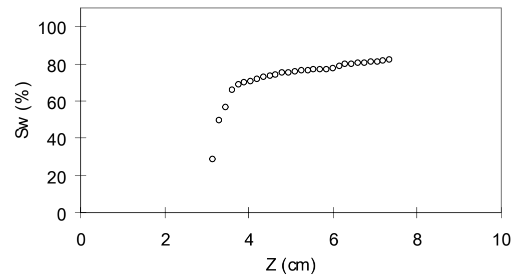

Figure 4. Water saturation distribution along the length (Z) of core #126 after centrifugation at 3000 rpm in water for 48 hours for imbibition capillary pressure measurement.

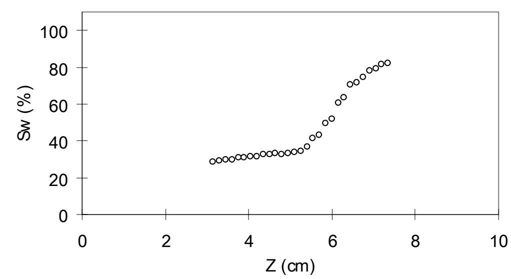

Figure 5. Water saturation distribution along the length (Z) of core #126 after centrifugation at 3000 rpm in oil for 48 hours for secondary drainage capillary pressure measurement.

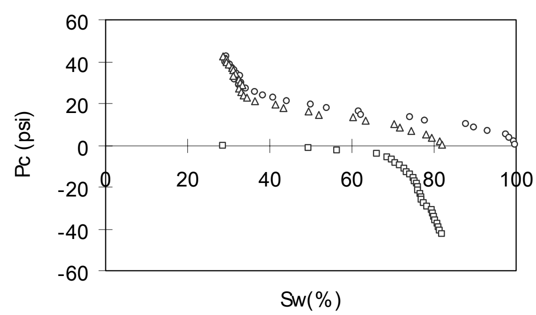

Figure 6. Primary drainage (○), imbibition (□), and secondary drainage (Δ) capillary pressure curves obtained by the single-shot method.

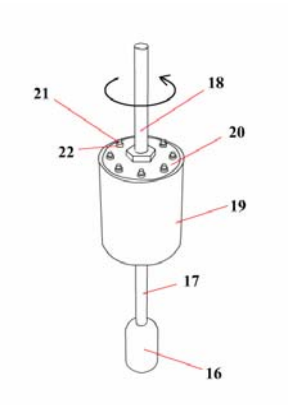

Figure 7. A schematic illustration of a spinning rock disk non-magnetic sample holder. 16: motor, 17: a drive shaft, 18: a rotational axis, 19: a rock disk holder, 20: a removable end closure, 21 and 22: a bolt and a nut for holding a rock disk. A circular arrow shows the spin direction of the rock disk holder. This sample holder is shown in a transverse section in the MRI magnet in Figure 8.

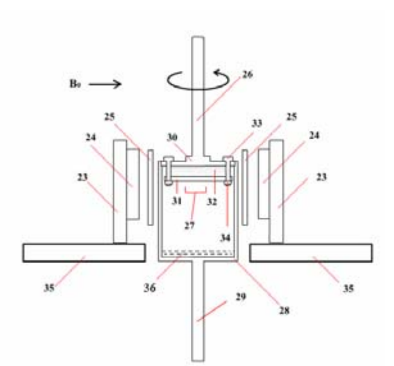

Figure 8. A schematic transverse section for a spinning rock disk non-magnetic holder within a permanent magnet MRI system. 23: a permanent magnet, 24: a gradient set, 25: RF coil, 26: upper spinning axis, 27: a rock disk holder, 28: a cup-like liquid collector, 29: lower spinning axis, 30: a upper rock disk holder plate, 31: a lower core disk holder plate, 32: a rock disk (typical diameter of 10-12 cm, thickness of 1-2 cm). 33 and 34: a bolt and a nut for holding the rock disk. 35: a platform to support the magnet, 36: liquid expelled from the rock disk outside the RF coil.

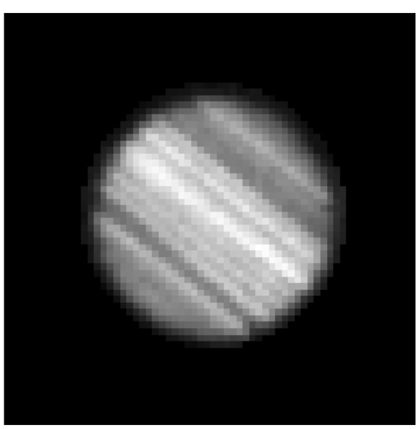

Figure 9. Spiral SPRITE MRI for a fully water saturated rock disk core.

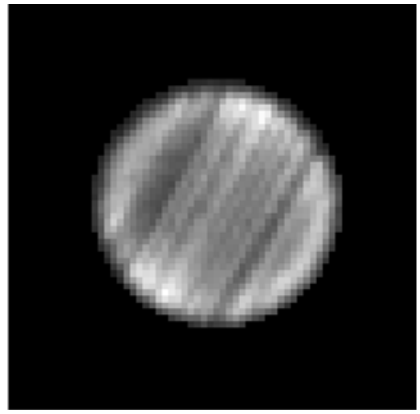

Figure 10. Spiral SPRITE MRI for a water saturated rock disk core #1 after centrifugation at 1920 rpm in air.

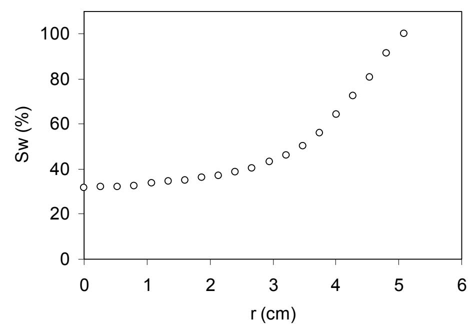

Figure 11. Water saturation distribution along the radii (r) of a disk core #1 after centrifugation at 1920 rpm in air.

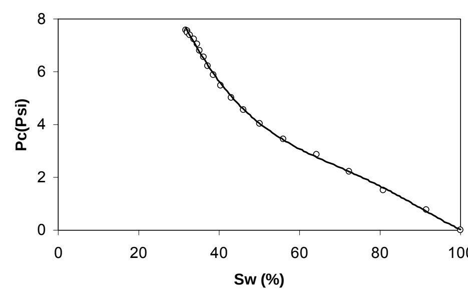

Figure 12. Capillary pressure curve of a disk core obtained by single-speed centrifuge and SPRITE MRI.