Magnetic Resonance Core Plug Analysis with the Three-Magnet Array.

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Abstract

A new approach for rock core plug measurements, employing a unilateral magnet with a solenoid as the RF probe is presented. The new benchtop instrument exploits the simplicity of the three-magnet array to explore measurement spots deeper inside the core plug. This approach avoids signal from the near surface region of the core plug, which is affected by cutting tools and may not produce reliable information. Core plugs of different lengths and diameters can be measured employing solenoids of different diameters as the RF probe. Results of porosity profile and T_{2eff} distribution measurements employing this approach are presented. A comparison of the behavior of a RF surface coil and solenoids of different diameters is also included. This low cost measurement with simple NMR hardware yields reliable core plug measurements.

Keywords: Unilateral magnetic resonance, Core plug analysis, Three-magnet array, Porosity measurement, T_2 distributions, UMR probes, Inhomogeneous field.

1. Introduction

Magnetic Resonance has a long history of applications in the petroleum industry due to the sensitivity of the NMR experiment to the fluids water, oil and gas which occupy the pore space of the rock matrix. Two general classes of experiments and instruments can be distinguished. The first class involves downhole NMR tools where an instrument is lowered into a borehole in the field, with a sensitive spot for measurement displaced into the rock matrix [1, 2, 3]. A variety of MR measurements can be undertaken to determine the local porosity, the type of fluids present, the mobility of the fluids and the pore size distribution [4, 5, 6, 7].

These measurements rely on the quantitative nature of the MR experiment, where the signal amplitude, neglecting relaxation time effects, is proportional to the quantity of ^{1}H bearing fluids. These results also exploit the ability of CPMG echo measurements to measure a T_2 distribution, which is well known to be an excellent proxy measurement for the fluid occupied pore size distribution.

The second class of MR core analysis measurement is a benchtop measurement of core plugs extracted from reservoir cores drilled as part of an exploration or production program. These core plugs may then be examined in a laboratory measurement, usually with low field permanent magnet based instruments.

Such instruments, common in the core analysis field, are based on closed magnets where the core plug is placed into the magnet structure for measurement. For this type of magnet it can be problematic to measure long core plugs like those obtained from the drilling process during the exploration of reservoirs. These magnets are also clearly limited in the sample diameter that can be accommodated.

This paper presents a new approach for this second class of measurements, employing a three-magnet array with a solenoid as the RF probe (Fig. 1). A three-magnet array [8, 9], with a homogeneous spot centered at a frequency of 2.25 MHz, and another with an extended constant gradient [9], centered at the same frequency, were employed. This frequency is similar to the value employed by the MR benchtop instrument previously described for core plug analysis in the laboratory.

Core plugs of different diameters can be measured employing solenoids of different diameters as the RF probe. In fact, a set of solenoids can be readily built according to the core plug to be measured. The measurement concept is similar to well logging NMR instruments (sample is removed from the magnet), but in this case the experiment is undertaken in the laboratory with a simple device. The measurement is undertaken from a specific spot inside the core plug (see Fig. 2), which avoids any signal from the surface. The near surface region is affected by the cutting tools and may not produce reliable information. As shown in this paper, despite the simplicity, the UMR measurement yields reliable results.

The UMR measurement has no limitation on the length of the core plugs that can be studied. Long core plugs can be analyzed by displacing the core plug inside the probe. Equivalently the magnet and RF probe may be displaced along the core plug. In this way longitudinal profiles of different parameters can be obtained. In addition, because the measurement spot is not radial symmetric inside the sample, transverse profiles can be also obtained by rotating the sample inside the probe.

A similar laboratory measurement approach has been proposed by Anferova et al. [10] based on a Halbach magnet design [11]. In this case the magnet encompasses the sample and is displaced along the core plug to obtain a longitudinal porosity profile of the sample. Nevertheless, the adjustment process for the Halbach magnet can be troublesome and time consuming. The fixed diameter of the magnet bore restricts the diameter of core plug that can be studied. Larger core plug diameters require building a new magnet which, as mentioned before, is not a simple process. Measurements employing Halbach magnets yield information about the full sample cross section, including regions close to the surface. In the Halbach magnet designs the introduction of magnetic field gradients, for spatial encoding to avoid the surface region, requires the introduction of magnetic field gradient coils and gradient amplifiers. This vastly increases the complexity of the instrument.

This paper presents the results of porosity profile and T_{2eff} distribution measurements employing a three-magnet array with a solenoid as the RF probe. We show that, despite the low cost and simplicity of the magnet, reliable results are produced. An additional comparison of the behavior of a surface coil and solenoids of different diameters is also included.

2. Experimental

All the UMR measurements were carried out with a LapNMR portable console (Tecmag, Houston, USA), connected to a 250 W RF power amplifier (TOMCO Technologies, Stepney, Australia) and a preamplifier (MITEQ, Hauppauge, USA). For the measurements, four solenoids of 4.2 (sol15), 5.5 (sol15h), 7 (sol25) and 9.5 cm (sol35) diameter and 2 cm length and a surface coil (sc) of 3 cm diameter (Fig. 1) were built. All probes were adjusted to have a loaded Q factor of 22. The tuning frequency and the Q were verified once the sample was placed inside the probe. No change of the Q was observed and the maximum frequency change was 4 kHz.

For comparing the probes single echo spin-echo measurements, with RF pulses of the same duration and an echo time of 500 μs, were employed. The voltage for the 90^o RF pulse was set at one half of the voltage for the 180^o RF pulse.

Core plugs (kokurek Industries, Caldwell, USA) of 1.5″, 2.5″ and 3.5″ diameter of each type in Table 1 were employed for measurements. The core plugs were fully saturated with brine (2%) in a container connected to a vacuum pump. The gravimetric method was employed for measuring the porosity in Table 1. Three composite core plug samples (CPS) were created of 1.5″ (CPS15), 2.5″ (CPS25) and 3.5″ (CPS35) diameter by combining core plugs of different porosities (Fig. 4). The core plugs were placed inside the CPS in order presented in Table 1.

For the profiling measurements, the CPSs were longitudinally displaced inside the RF probe in steps of 1 cm for CPS15 and 2 cm for CPS25 and CPS35. At each spatial point a 2000 echo CPMG measurement was undertaken. The porosity was determined from the T_{2eff} distribution obtained from the CPMG measurement calibrated by a reference sample. The T_{2eff} distributions were processed by inverse Laplace transformation of the CPMG echo trains. For each CPMG echo 128 time domain points were acquired. The first point of the CPMG decay was determined as the maximum of the first echo. Subsequent CPMG points were measured at multiples of the echo time (500 μs). The repetition time TR = 5 s was set according to the T_1 of the Bentheimer core plug which is the longest T_1 in the CPS. The number of scans was 128, 256 and 512 for CPS15, CPS25 and CPS35 respectively. The measurement durations at each spatial point of the CPS were 12 min, 25 min and 50 min respectively. The RF pulse lengths were set according to Table 2. The Berea core plug with porosity of 21 % was employed as the reference sample.

Finally, a porosity and T_{2eff} profile of a long XXX core plug (Fig. 5) of 6.35 cm (2.5″) diameter and 59 cm of length was obtained. The core plug was saturated employing a home-made container, filled with distilled water, connected to a vacuum pump. The core plug was displaced inside the solenoid (sol25) with steps of 2 cm for a total of 30 measurement points. For each point a 2000 echo CPMG train with 256 scans was acquired. The echo time was 600 μs and the repetition time 5 s. The time of measurement for each point was 27 min. The employ of the maximum power of the RF amplifier (250 W) allowed reducing the pulse length to 11 μs for this measurement.

For measuring different fluids in the pore space of a core plug two different water/oil ratios were evaluated in a 1.5″ diameter Berea core plug. The solenoid sol15h was employed for this experiment in order to measure the core plug inside a core holder. A 256 scan CPMG acquisition was undertaken in a uniform spot three-magnet array with echo time of 500 μs and 2000 echoes. The RF pulse length was 12 μs. The time of measurement was 5 min. For comparison, after each experiment the same sample was measured in a 2 MHz homogeneous magnet with a MARAN Ultra console (Oxford Instruments, Abingdon, UK).

3. Results and Discussion

3.1 Choosing the RF probe

A near surface UMR measurement is best avoided since this region of the core plug is affected by the cutting tools. A deeper sensitive spot is required. This requirement is a challenge for surface coil RF probe. The rapid decay of B_1 with distance from the coil requires the employment of high power and/or long duration RF pulses in order to excite the desired region properly. Both factors can be troublesome. High power RF pulses require high quality capacitors for tuning the RF probe in order to avoid arcing during the excitation. Long duration RF pulses reduce the excited spot size compromising SNR during reception.

For the three-magnet array a solenoid can be employed as the RF probe. The solenoid, in addition to a more homogeneous B_1, presents higher sensitivity than the surface coil for deeper regions. Nevertheless, for large diameter core plug samples the necessity of higher power or longer RF pulses can produce the same undesirable effects described for the surface coil. The small size of the spot in comparison with the probe diameter, can also compromise the SNR during the experiment.

A comparison among three solenoids of different diameters and a 3 cm diameter surface coil was undertaken. A spot placed at a fixed distance from the surface of the magnet was explored. The three-magnet array with homogeneous spot at 2.5 cm from the surface, centered at a frequency of 2.25 MHz, was employed for this measurement. Three Bentheimer core plugs, fully saturated with brine (2%), of 1.5″, 2.5″ and 3.5″ diameter were employed as test samples.

Table 2 shows the results of the comparison. Even the largest radius solenoid produces more signal than the surface coil. The surface coil was tested with the 1.5″ diameter sample only. The excitation power was kept at the same value for all the measurements. The pulse length for the surface coil is less than for the sol25 and sol35 solenoids, which means a higher B_1 for equivalent power. The smaller signal for the surface coil can be associated with the fact that, because of the rapid decay of B_1 with distance, only thin layers of the sample are excited with the proper B_1. For the solenoid the entire sensitive spot is excited with the same B_1 and therefore more signal is available during reception. The smaller diameter solenoid sol15 produces the highest signal becafuse of its highest B_1. Higher B_1 means highest sensitivity by reciprocity and allows shorter RF pulses (8 μs) which excite larger spots for the measurement. The level of noise was similar for all acquisitions.

3.2 Exploring deeper spots inside the sample

Deeper spots inside the core plug can be explored by employing a three-magnet array with extended constant gradient through appropriate choice of the resonance frequency. Figure 3 shows the magnetic field distribution along the vertical central line over the array. The constant gradient of 60 G/cm covers a distance of more than 4 cm. In this case two solenoids (sol25 and sol35) and the surface coil were employed in order to explore the centre of three Berea core plugs of 2.5″ and 3.5″ diameter.

Table 3 shows the amplitude of the echo signal obtained with a single echo spin-echo sequence. The depth of the measurement spot was measured from the surface of the core plug. The surface of the core plug is 4 mm from the magnet surface. The core plug of 1.5″ was not employed for this measurement because the distance to its centre is 2 cm, which is closer than the position of the homogenous spot previously explored. For these experiments the number of scans was increased to 1024 because of the reduced signal amplitude. The presence of the gradient reduces the size of the spot in comparison to the homogeneous spot magnet. For a probe with 100 kHz of bandwidth (Q = 20) and RF pulses less than 10 µs the measurement spot is reduced in the vertical direction ($\boldsymbol{y}$) from a width of 1.5 cm to 0.4 cm by the constant gradient. In the horizontal directions ($\boldsymbol{x}$, $\boldsymbol{z}$) the spot remains the same size.

For the surface coil the RF pulse duration was varied from 10 to 50 µs, but no signal was obtained from the centre of the core plugs. The surface coil is limited to a depth of approximately 2 cm. The solenoid is a better choice to explore deep layers inside the core plugs.

3.3 Measuring porosity in composite core plugs.

For this measurement long core plugs were imitated by employing composite core plug samples. The length and porosity of the core plugs inside the CPS were previously determined (Table 1) which allowed a better evaluation of the UMR measurement. The CPSs were displaced longitudinally inside the probe and a CPMG measurement was obtained from each measurement point.

Figure 6a shows the T_{2eff} distribution functions from the composed core plug sample of 1.5″ employing the solenoid sol15 and the homogeneous spot three-magnet array. Figure 6b shows the porosity profile obtained from these functions. All porosity values were obtained employing a 21 % porosity reference sample. The dashed vertical lines represent the limits of the different core plugs inside the

CPS. Each measurement point is separated by 1 cm. There is a clear discrimination of porosity inside the CPS. The porosity for the first and last point of the profile has been underestimated because the portion of the CPS is smaller than the sensitive volume of the probe and therefore smaller than the reference. The sharpness of the transition bands has been affected by the length of the sensitive spot of the probe (2 cm).

A T_{2eff} profile of the CPS is presented in Fig. 6c. Only the T_{2eff} corresponding to the highest peak of the T_{2eff} distribution was chosen for display to show the contribution of the more representative pore size inside the sample.

Porosity profiles were also obtained for CPS25 and CPS35. These types of long core plugs are usually more difficult to measure in closed magnets because of their large diameter (2.5″ and 3.5″ respectively). Figure 7 shows the porosity and T_{2eff} profile for CPS25 and Fig. 8 for CPS35. In these cases the separation between successive measurement points was 2 cm.

Special attention should be directed to the section of the CPS corresponding to the Indiana Limestone core plug (number 2). The variations in the profiles suggest the presence of inhomogeneities along the sample. A homogeneous field experiment was conducted in an 8 MHz closed magnet employing the spin-echo SPI method with a MARAN DRX HF console (Oxford Instruments, Abingdon, UK) in order to confirm this behavior. Figure 9 shows T_2 distributions obtained from different transverse planes of this core plug. Different distributions at different planes confirm the presence of inhomogeneities along the sample which explain the differences in the profiles.

The results obtained for the porosity profiles agree with the values in Table 1 and are consistent for the three core plug diameters. Core plugs of the same type where extracted from the same block, therefore similar profiles where expected for the three diameters.

3.4 Measuring porosity in a realistic long core plug.

A final porosity measurement was undertaken employing a long XXX core plug. This measurement does not collect information from the surface of the core plug. Figure 5 shows the irregular surface of the core plug because of the effect of the cutting tools. A porosity measurement from the whole transverse section of the sample would be affected by these irregularities. The white spots in the picture are Teflon marks employed for other measurements.

Our approach exploits the well localized measurement spot of the three-magnet array with homogeneous spot. Figure 10 shows the position of the measurement spot inside the sample. The spot dimensions are defined by the B_0 field distribution of the magnet, the bandwidth of the excitation RF pulse (91 kHz) and the receiver bandwidth (50 kHz). Even though the shape of the spot is not a perfect rectangle as presented in Fig. 10, this representation includes most of the transverse measurement area inside the sample. This type of localized measurement can produce longitudinal profiles by displacing the sample inside the probe and, because the measurement spot is not radial symmetric inside the sample, transverse profiles can be also obtained at any position along the longitudinal axis by rotating the sample inside the probe.

Figure 11a shows the T_{2eff} distribution functions obtained from 30 points along the core plug. Figure 11b shows the porosity profile and Fig. 11c the T_{2eff} profile. The results show a good homogeneity along the sample. The variation at the end of the profiles was verified by flipping the sample inside the probe to discard any mechanical artefact and confirmed in a homogeneous field MRI system. Figure 12 shows the transverse porosity and T_{2eff} profiles obtained at 15 cm from the extremity of the sample. The sample was rotated clockwise inside the probe with steps of 30°.

3.5 Measuring different fluids in the pore space of a core plug employing the three-magnet array.

The simplicity of the proposed configuration, employing a three-magnet array in combination with a solenoid, can be also exploited for measuring dynamic process in the pore space of a core plug. In order to evaluate this possibility a 1.5″ diameter Berea core plug, firstly saturated with brine (2 %), was flooded with an oil phase. Two measurements were undertaken for different water/oil ratios employing the proposed unilateral measurement and a homogeneous field 2 MHz desktop Maran Instrument (Oxford Instruments, Abingdon, UK). For each measurement the results from both instruments were compared.

For the first measurement the core plug, previously saturated with brine (2 %) was flooded with dodecane, at a flow rate of 0.3 ml/min. After three hours, the total production of water was 11.7 ml. The water saturation (Sw) was thus 59.9 % and the oil saturation (So) was 40.1 %. In the second measurement the flow rate was increased to 10 ml/min. After two hours, the total production of water was 17.1 ml. The water saturation (Sw) in this case was 41.8 % and the oil saturation (So) was 58.2 %.

Figure 13 shows the T_2 distribution for the full brine saturated (dotted), the first (dashed) and the second (solid) water/oil ratio sample. Figure 13a represents the T_2 distribution for the measurements in homogeneous field and Fig. 13b for the homogeneous spot three-magnet array. For the unilateral measurement the CPMG echo train was acquired from the centre of the core plug. For the experiment with the 2 MHz desktop Maran Instrument the measurement was from the entire core plug.

The Berea sample under test is known to be water wet. The relaxation ratio of water in the pore space is higher and the T_2 distribution is shifted to shorter T_2s than is the case for dodecane with a reduced surface effect. With the continuous flooding of dodecane, the movable water is displaced by dodecane, the saturation of dodecane increases and the right peak shifts to longer T_2 component. The right most peak of the dashed curve corresponds to dodecane, the left most part of the distribution corresponds to water that is difficult to displace. There is a slight overlap between the T_2 distribution of movable water and dodecane. From the solid curve, the dodecane phase and the water phase can be separated clearly by the T_2 distribution. The right peak of the T_2 curve corresponds to dodecane. The left peak corresponds to irreducible water. The volume of oil and water in the core plug can be estimated by the area under the curve in the T_2 distribution. The water saturation has been reduced from 100% to 59.9% and then to 41.8% by flooding. These are close to the values determined from the production data (57.7% and 38.6%). We do not achieve a reliable measure of irreducible water saturation, because the inlet pressure (15 psi) is not high enough to displace all the movable water.

4. Conclusions

This paper has shown that the three-magnet array is a very simple and reliable tool for core plug analysis, both static survey measurements and monitoring of dynamic process. Porosity and T_{2eff} profiles as well as T_{2ff}

distributions have been obtained. We have shown that long core plugs of different diameters can be easily characterized employing this approach by simply changing the RF probe employed. The solenoid, easy to build, is a much better approach than the surface coil in order to explore deeper layers inside the sample. In addition to the higher sensitivity, the more homogeneous B_1 permits a better excitation of the measurement spot which increases the level of the signal during reception.

It has been shown that, even though the three-magnet array with an extended constant gradient reduces the size of the measurement spot and therefore reduces the SNR, it is a reasonable option for exploring very deep layers inside the core plug.

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Figure captions:

Figure 1. Three-magnet array with constant gradient, similar in size and weight to the homogenous spot version, surface coil and solenoid RF probes for measuring core plugs of 1.5″, 2.5″ and 3.5″.

Figure 2. Schematic of the measurement employing the three-magnet array. The measurement in undertaken from a specific spot inside the core plug. The core plug is ideally displaced from the core plug surface.

Figure 3. Magnetic field along the vertical central line of the three-magnet array with constant gradient. The strength of the constant gradient is 60 G/cm in the region from 2.5 to 7 cm.

Figure 4. Composite core plug sample of 3.5″ diameter created from individual core plugs of different types of rocks. From left to right Berea, Indiana Limestone, Bentheimer and Nugget sandstone core plugs held together with a heat shrink tube and two Teflon caps at the end to seal.

Figure 5. Real long core plug XXX type of rock. The surface of the sample shows visible effects of the cutting tools.

Figure 6. Porosity (b) and T_{2eff} (c) profiles of CPS15 extracted from the T_{2eff} distributions (a) obtained with the three-magnet array with homogeneous spot. The four core plugs forming the CPS are clearly differentiated. The vertical dashed lines mark the actual limits of the core plugs in the CPS (see Table 1).

Figure 7. Porosity (a) and T_{2eff} (b) profiles of CPS25 obtained with the three-magnet array with homogeneous spot. The vertical dashed lines mark the actual limits of the core plugs in the CPS (see Table 1).

Figure 8. Porosity (a) and T_{2eff} (b) profiles of CPS35 obtained with the three-magnet array with homogeneous spot. The vertical dashed lines and the numbers in the top part of the figure represent the position of the core plugs in the CPS (see Table 1).

Figure 9. T_2 distribution, spatially resolved, measured in a homogeneous field MRI instrument, for transverse planes at 1 cm (a), 4 cm (b), 7 cm (c) and 9 cm, along the longitudinal axis of the Indiana core plug. The variations with position show the sample is significantly inhomogeneous.

Figure 10. Long core plug XXX on the unilateral magnet. The homogeneous spot defined by the magnetic field distribution, the RF pulse and the receiver bandwidth is more than 1 cm inside the sample. The position of the measurement spot allows obtaining longitudinal profiles by displacing the sample or transverse profiles by rotating it.

Figure 11. T_{2eff} distributions (a) measured along a real core plug employing the homogenous spot three-magnet array as well as porosity (b) and T_{2eff} (c) profiles obtained from it. The T_{2eff} profile shows only the most representative T_{2eff} value for each position.

Figure 12. Transverse porosity (a) and T_{2eff} (b) profiles obtained with the three-magnet array with homogeneous spot by rotating the long core plug

XXX inside the probe. The profiles were obtained at 15 cm from the extremity of the core plug.

Figure 13. T_2 distributions for different water/oil ratios, observed in a 2 MHz homogenous field magnet (a) and employing the homogenous spot three-magnet array (b). Line (--) represents the T_2 distribution for the first water/oil ratio (59.9% water and 40.1 % oil) and (-) for the second ratio (41.8% water and 58.2 % oil). Line (…) shows the T_2 distribution for the brine saturated sample.