Determination of rock core wettability by NMR

Technical Paper

Introduction

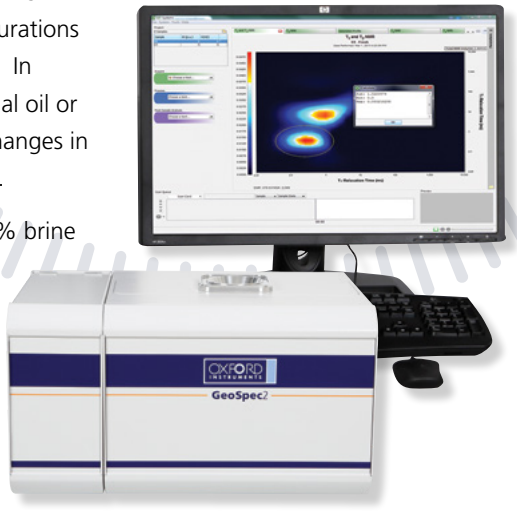
One of the most important parameters in predicting the output of an oil reservoir is wettability. This parameter can vastly affect the ease with which the reservoir can be produced; but despite its importance, there are very few methods for getting an accurate wettability measurement. In this technical paper, a new method for measuring wettability using NMR is presented.

Wettability can be thought of as the tendency of a surface to maintain contact with a fluid. Inside the pores of a rock, this tendency of the surface can favor either water or oil adherence to the surface of the pores. Quantitatively this can be defined as [1],

$$I_w = \frac{A_w - A_o}{A_w + A_o} \quad [1]$$

where I_w is the wettability index, A_w is the surface area wetted by water and A_o is the surface area wetted by oil. From the equation it is obvious that if more surface area is wetted by water then I_w = 1 to 0 and the rock is said to be water wet. Conversely, if there is more surface area wetted by oil then I_w = 0 to -1 and the rock is said to be oil wet. Wettability is a crucial petrophysical parameter for determining accurate production rates in oil and gas reservoirs. However, industry standard wettability measurements (Amott Test and USBM) are expensive and time consuming.

It is known that NMR response varies as a function of wettability change in rock core plug samples [1-5]. This information was used to develop an NMR wettability index (NWI) based on T_2 distributions [6,7]. This NWI is also capable of measuring changes in wettability as a function of oil/water saturations unlike traditional methods which are based on measurements at S_{wi} and S_{or} only. In addition, these oil/water saturations are determined without the aid of any special oil or brine, such as D_2O. This allows the NMR method to nondestructively monitor changes in wettability in real time (i.e. during a flooding experiment or an aging procedure).



In order to derive this NWI based on T_2 distributions, the NMR T_2 spectra of 100% brine saturated, 100% oil saturated, bulk oil and bulk brine are needed. These spectra are then mixed to give a predicted T_2 spectrum which is compared (via a least squares fit) to a T_2 spectrum recorded from a sample partially saturated with both water and oil and whose wettability is to be determined. In this application note, we present a new method which couples this T_2-based NWI to spatially resolved T_2 NMR measurements to monitor changes in wettability and saturation along rock core plugs.

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Method

To determine the spatially resolved NWI of a sample whose wettability is unknown, the following procedure was followed.

1. Record T_2 and spatial-T_2 spectra of the mixed saturation (i.e. brine/oil) sample whose wettability is to be determined. For example, an "as received" sample or one which was saturated in the lab with both oil and brine.

2. Clean and dry the sample. Saturate the sample to 100% with brine. Record the T_2 and spatial-T_2 spectra of the 100% water saturated sample ($S_{w\text{-}100\%}$).

3. Clean and dry the sample. Saturate the sample to 100% with oil of interest. Record the T_2 and spatial-T_2 spectra of the 100% oil saturated sample ($S_{o\text{-}100\%}$).

4. Record the T_2 spectra of bulk brine and oil ($S_{w\text{-}bulk}$ and $S_{o\text{-}bulk}$).

For this work, a sample of mixed saturation and unknown wettability was created by first saturating a sandstone to 100% water saturation. The $S_{w\text{-}100\%}$ sample was then centrifuged for approximately 12 hours surrounded by dodecane. This resulted in a sample of mixed saturation (S_{mix}) and spinning the same sample at different speeds resulted in samples of differing dodecane/brine saturations. All NMR measurements were completed on an Oxford Instruments GeoSpec 2$^+$-75 rock core analyser [8]. Acquisition and processing of the NMR data was achieved via Green Imaging Technologies software, GIT Systems Advanced [9].

Data Analysis

Figure 1 shows the 100% oil saturated (orange trace), 100% brine saturated (blue trace), bulk brine (red trace) and bulk dodecane (green trace) T_2 distributions for the sandstone sample analysed in this work. Also shown in Figure 1 is the T_2 distribution of the sample of mixed saturation and unknown wettability (brown trace).

The predicted T_2 distribution (Figure 1 – black trace) is generated by varying the contributions from the 100% oil saturated, 100% brine saturated, bulk brine and bulk dodecane T_2 distributions via the following equation:

$$S_{pred} = WHS_{w-100\%} + (1-W)(1-H)S_{o-100\%} + (1-W)HS_{w-bulk} + W(1-H)S_{o-bulk} \quad [2]$$

The contributions from each T_2 distribution are controlled by the H and W functions. The typical forms of these equations are plotted as the light blue (H) and pink lines (W) in Figure 1. These functions are like step functions, where, for example, all pores to the left of the inflection point of the W function are wetted by water and all the pores to the right of the inflection point of the W function are wetted by dodecane. Conversely all the pores to the left of the inflection point of the H function are occupied by brine and all the pores to the right of the inflection point of the H function are occupied by dodecane. In a least-squares fit, the position of these functions is allowed to vary (left and right on the T_2 axis) until there is good agreement between the predicted and measured T_2 distributions of the sample of mixed saturation and unknown wettability. Figure 2 shows the contributions to the final predicted T_2 distribution (Figure 1) from the $S_{w\text{-}bulk}$, $S_{o\text{-}bulk}$, $S_{w\text{-}100\%}$ and $S_{o\text{-}100\%}$ T_2 distributions. Once the final H and W functions are known they are used to generate the predicted saturation and wettability index for the

sample of mixed oil/brine saturation. For the data shown in Figure 1 and 2, this corresponds to a water saturation of 13% and wettability index equal to 0.89 (water wet). The data analysis was initially done in Matlab but was later implemented into Green Imaging Technologies software [9].

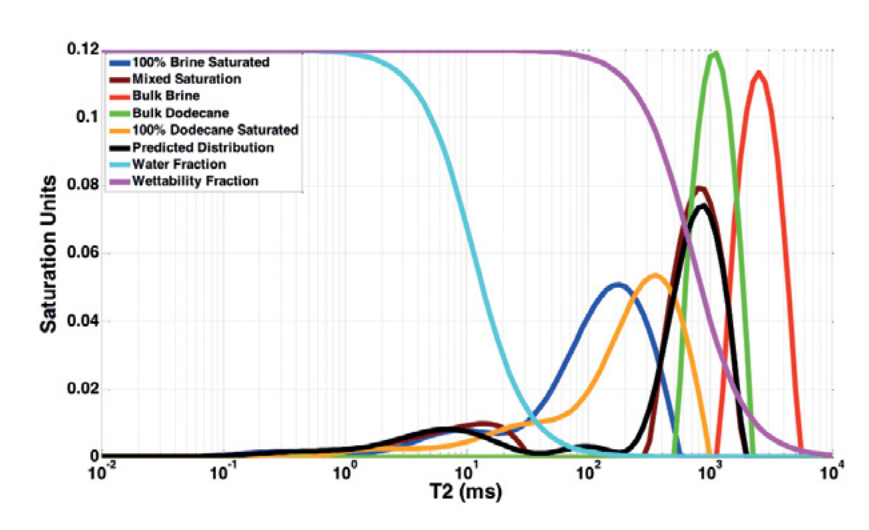

***Figure 1**: Typical bulk-T_2 spectra used for wettability determination. The brown T_2 spectrum is recorded from the mixed wettability sample whose wettability is to be determined. The 100% brine saturated (blue), 100% dodecane saturated (orange), bulk dodecane (green) and bulk brine spectra (red) are then combined to give the predicted T_2 distribution (black). The combination is done via use of the water (light blue) and wettability fraction functions (pink).*

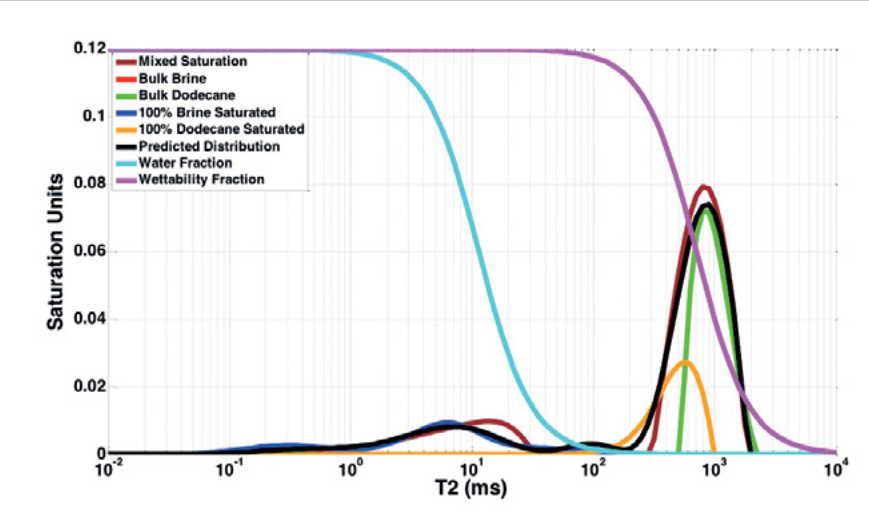

***Figure 2**: Bulk T_2 spectrum (black) predicted from wettability fitting along with the measured bulk T_2 spectrum (brown) are shown. Also shown are the contributions to the predicted spectrum from the bulk dodecane (green), 100% dodecane saturated (orange) and 100% brine saturated (blue) spectra are also shown. The water fraction (light blue) and wettability fraction (pink) are also shown.*

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Data Analysis *continued*

The previous explanation of the wettability analysis was for bulk T_2 distributions which cover the entire length of the rock but this explanation applies also to the spatial-T_2 wettability analysis. The spatial analysis proceeds in the same manner as the bulk analysis but the 100% oil saturated, 100% brine saturated, and mixed saturation T_2 distributions are for a given slice of the rock. Figure 3 shows a typical stack plot for a S_{mix} spatial-T_2 distribution along with an intensity plot (Figure 3-inset) generated from the same data. For example, the least-squares fit is then performed, minimising the difference between S_{mix} (slice 1) – S_{pred} using Equation 2 to generate S_{pred} where $S_{w\text{-}100\%}$ and $S_{o\text{-}100\%}$ are now from the first slice of their spatial-T_2 distributions. The least squares fit will result in H and W functions for slice 1. Wettability and saturation for the first slice are then derived for that slice from these H and W functions. This procedure is repeated until each slice of the spatial-T_2 distributions has been analysed and I_w and saturations as a function of position in the rock have been created.

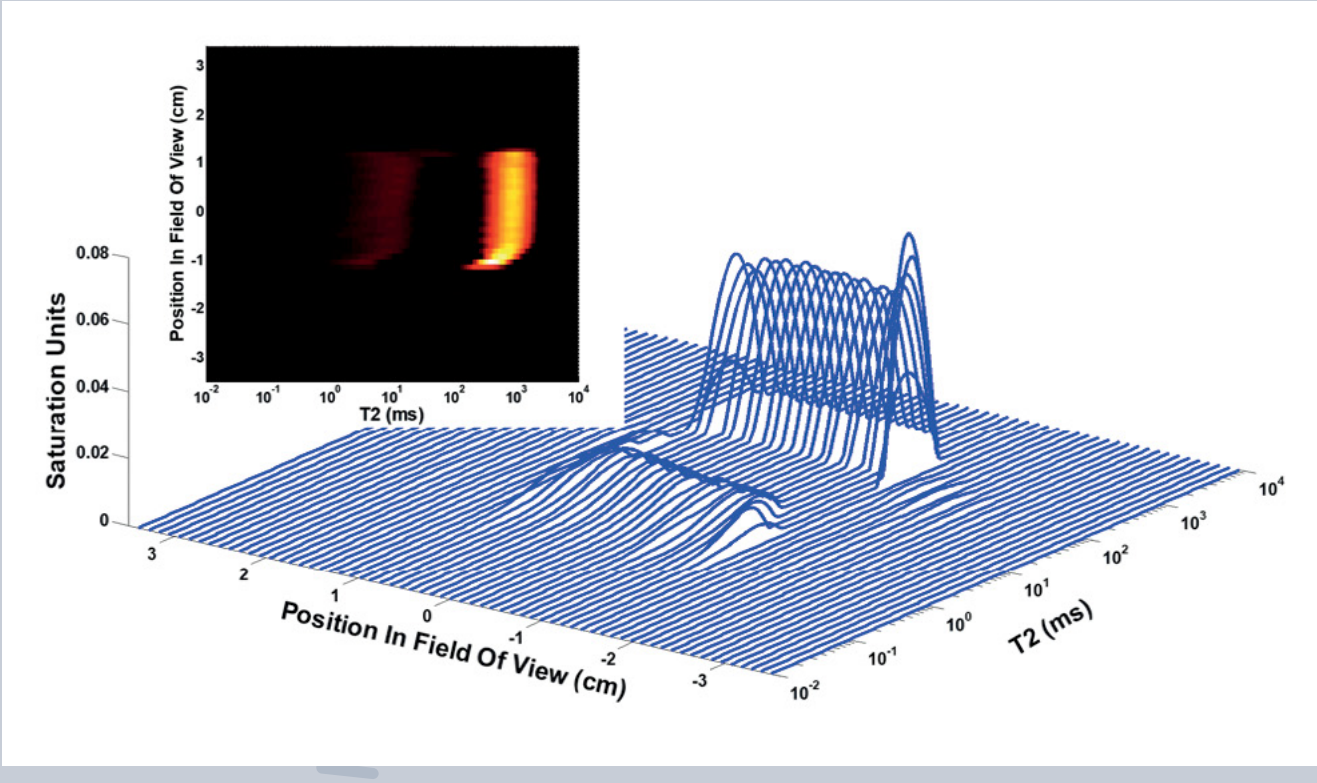

Figure 3*: Spatial-T_2 spectra for the same sample as the bulk spectra in Figure 1. The inset shows the intensity plot generated from the spatial-T_2 data. The intensity plot is a top view of the spatial-T_2 data where the intensity of each pixel corresponds to the magnitude of the T_2 distribution at that position in the rock.*

Results

Figure 4 shows the spatial-T_2 wettability analysis completed on the sandstone sample. The upper plots show the spatially dependent wettability (blue traces) and saturation (red traces) profiles derived for each centrifuge speed tested. The rocks began at 100% brine saturated and had dodecane spun into them from left to right on the upper plots of Figure 4. Also shown in the upper panels of Figure 4 are the saturation profiles (black traces) derived from separate measurements where the rock was initially saturated to 100% with D_2O rather than H_2O before having dodecane spun into them. Employing NMR invisible D_2O allowed the saturation profiles to be derived directly from the NMR data. It should also be noted that because D_2O is denser then H_2O, the centrifuge speeds were reduced to match the capillary pressures employed with H_2O. These D_2O profiles were

continued overleaf

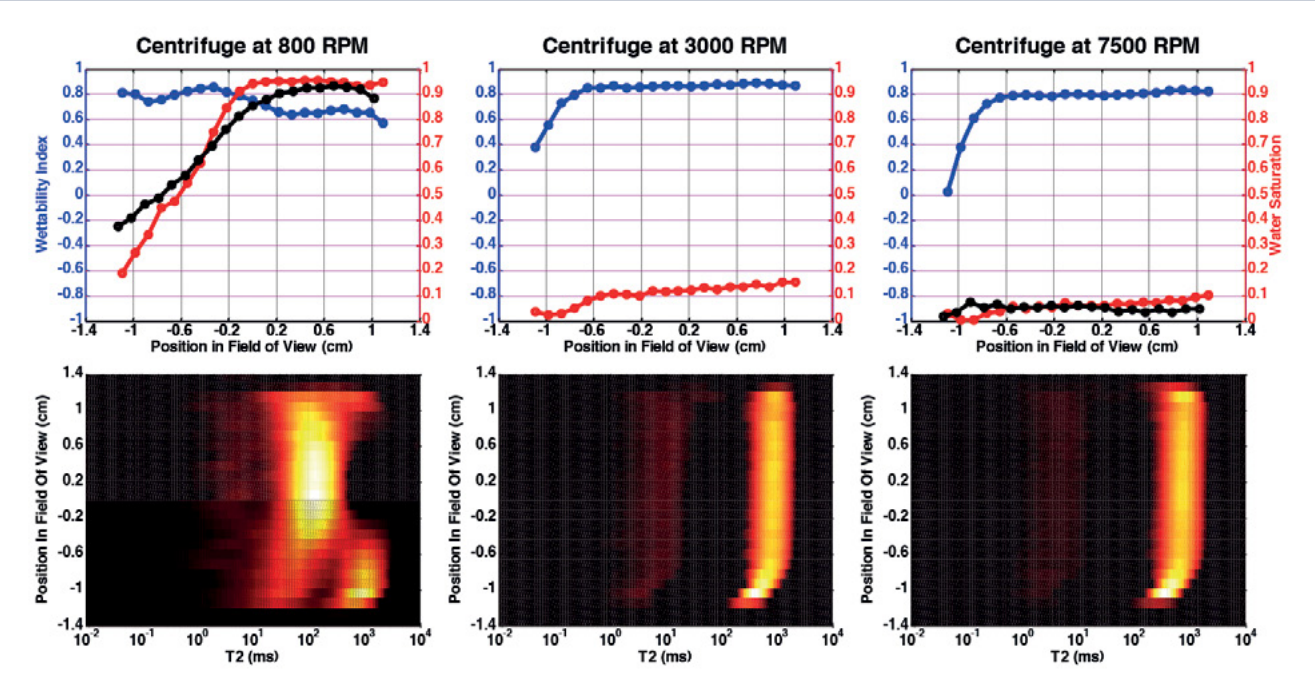

***Figure 4**: The predicted wettability (blue) and saturation (red) profiles for rock 109S are plotted in the upper panels. Samples of differing saturations were manufactured by spinning dodecane into 100% brine saturated samples at differing centrifuge speeds (800, 3000 and 7500 RPM). The dodecane entered the rock from left to right as observed on the upper plots. The black trace corresponds to the saturation profiles measured using the same samples initially saturated with D_2O in lieu of H_2O. The lower panels show the intensity plots generated from the spatial-T_2 data from the mixed saturation samples.*

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Results *continued*

then used to independently verify the accuracy of the profiles derived from the wettability fitting. There is no similar method for verifying the wettability as a function of position. The lower panels of Figure 4 show the intensity plots created from the spatial-T_2 data for the mixed saturation samples tested at each centrifuge speed.

For 800 RPM, the saturation profile derived from wettability fitting agrees well with that measured using D_2O. There is clearly a saturation gradient along the length of the rock. The average saturation for the rock is 0.71. The wettability on the other hand does not show the same variability with position. It is relatively constant across the rock independent of both position and water saturation. The average wettability across the rock is 0.73 making the rock water wet. For 3000 RPM, the saturation across the rock is now relatively uniform and significantly reduced as compared to 800 RPM. The average saturation is now 0.11 and the average wettability is now 0.82. D_2O data was not recorded at 3000 RPM so there is no comparison between the predicted and measured saturation profiles. For 7500 RPM, the saturation and wettability are again uniform along the rock. The average saturation is now 0.06 and the saturation profile agrees well with the corresponding D_2O saturation profile. The average wettability is now 0.73. Both the saturation and wettability have decreased only slightly as compared to 3000 RPM.

While no other technique exists for measuring wettability as a function of position, the average wettability derived from the spatial-T_2 data can be compared with wettability determined from other methods such as the Fleury NMR method [1] and an Amott test. These comparisons were completed for the sandstone sample and the results are summarised in Table 1. For the sake of this comparison, the 7500 RPM data was used. While there is no reason to think the absolute value for the wettabilities derived from each method summarised in Table 1 should be equal, there should still be consistency in the wettability predicted for each rock. This is true for the data summarised in Table 1 where each method indicates that each rock is water wet.

Wettability Technique	Wettability
Average wettability from Spatial-T_2 (this work – 7500 RPM)	0.73
Fleury NMR Method	0.43
Amott Test	0.21

***Table 1**: Wettability Comparisons*

Conclusion

A new method for determining the wettability as a function of position in a core sample has been presented. This method couples the wettability determination via NMR T_2 distributions method first presented by Looyestijn et al. [6,7] with spatial-T_2 data. Using this method, we have successfully determined the wettability as a function of position for a sandstone sample with mixed oil/water saturations. This new measurement opens a new range of wettability-based experiments, including the ability to track wettability during a flooding experiment, as well as measuring wettability at different saturation levels during one measurement from one sample.

Signal intensive measurements such as the spatial T_2 measurement used here have been impractical on previous generations of NMR instruments due to long measuring times. Advancements in instrument design and performance, such as those found on the GeoSpec+ product line, now make these measurements possible.

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