Porosity and Permeability Calculation Using NMR Logging in an Iraqi Oil Field

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Abstract. This study aims of analysing the NMR data and extracting the petrophysical properties of a well in an Iraqi oil field. T2 analysis forms the basis of more complex analysis for the interpretation of NMR, including wettability analysis, facies discrimination and the identification of reservoir units from NMR data. T2 analysis can also be used to calculate porosity, calculate the geometric mean of the distribution, track the position of the modes (peaks of the distribution), and estimate fluid viscosity. NMR logging data has been used for an Iraqi oil field and interpreted to calculate PHIT, PHIE, BVI, CBW, FFI and K. In this current research the petrophysical properties have been calculated and the moveable fluid zone has been detected, where the porosity and permeability values are significant with a good value of FFI which represents the reflection of high value of T2.

1. Introduction
Basically NMR is an acronym for Nuclear Magnetic Resonance. Nuclear Magnetic Resonance relies on a simple principle that the molecular behaviour of materials can be affected by a magnetic field [1]. The best model for describing this behaviour is to consider nuclei as bar magnets. In order to be able to align certain nuclei with magnetic properties in a magnetic field [1].

These nuclear bar magnets have two important properties:

- A magnetic moment, which determines the strength of the interaction.
- Spin: in a magnetic field, the nuclei spin which causes the nuclear bar magnet to precess around the applied magnetic field. The nuclear spins process at a frequency that is dependent on the strength of the magnetic field. Thus, the nuclear spin possesses a resonance frequency that is related to the strength of the magnetic field, hence the term Nuclear Magnetic Resonance [1].

NMR is seen to be interest to the formation evaluation specialist because the behaviour of the nuclear spins is related to:

- The properties of the fluid—most importantly the chemical composition of the fluid, and the viscosity of the fluid.
- Where a fluid is contained in a porous medium, the interaction of the nuclear spins with the pore surface perturbs the behaviour of the nuclear spins.

   In rocks, the overall magnetization of a fluid is related to pore size and fluid composition. By knowing the pore size distribution, it is possible to derive the bound fluid volume which can be used, in turn, to derive permeability.

   The NMR measurement used in the petrophysical analysis of rocks utilizes three different applied magnetic fields:

1. A static magnetic field \(B_0\).
2. A magnetic field generated using oscillating radio frequency pulses (\(B_1\)). This field is applied normally (at right angles) to the static \(B_0\).
3. Local magnetic field fluctuations which are generated by unpaired electrons and neighbouring nuclei.

   Detection of magnetization decay in the transverse plane is referred to as the "transverse relaxation" or the "T2 relaxation". In the case of formation evaluation, the NMR experiment basically examines the time taken for the protons' spins to relax from \(B_1\) to \(B_0\) by detecting magnetization in the transverse plane.

2. **T1 versus T2 Relaxation**

   T2 relaxation is related to the detection of the proton spins in the transverse plane which is aligned with the \(B_1\) field. T1 relaxation relates the time taken for the proton spins to translate from a random alignment to become aligned in the direction of the \(B_0\) field.

   The difference between T1 and T2 can be considered as the measurement of relaxation to \(B_0\) in two different measurement directions. T1 looks in the direction of \(B_0\) and normal to \(B_1\). T2 looks in a direction normal to \(B_0\) and parallel to \(B_1\) (i.e., T1 refers to the y-z plane and T2 refers to the x-y plane). [2]

3. **Understanding T2 Distributions**

   The distribution of exponentials, or T2 distribution, can be interpreted in terms of pore size and the composition of the fluid residing in the pore. [2] Figure 1

![Figure 1. T2 distribution in relation to pore size and fluids [2]](image)

4. **Subdivision of the T2 Distribution:**

   It has been noticed that the T2 distribution is subdivided on the basis of pore size and fluid type. The shortest relaxation times contain clay and capillary bound water, collectively referred to as the bound fluid volume (BFV). Moreover, the BFV can be determined by applying a T2 cutoff. The use of a T2 cutoff relies on the assumption that bound fluid resides in the smallest pores. For sandstones, this is usually quoted as 33ms and for carbonates, 100ms is often used. [3]

   Clay bound water (CBW) is often estimated by using a 3ms cutoff. In terms of NMR interpretation, the bound volume irreducible (BVI) is defined as capillary bound water which is
calculated from BFV - CBW.

The T2 cutoff can be calibrated using NMR measurements on core samples. Core samples are analyzed at 100% brine saturated conditions. De-saturating the core by using a centrifuge or porous late method can be used to determine Swirr. The Swirr value can be used to determine the appropriate T2 cutoff for the brine-saturated rocks.

The desiderated core may be measured by using NMR to confirm that the bound does actually reside in the smallest pores. [2]

Furthermore, the unique information, such as BVI and CBW, provided by NMR logging can significantly enhance the estimation of resistivity-based water saturation and can greatly assist in the recognition of pay zones that will produce water-free. [1]

In the NMR literature, the concept of bound water (BVI) is used in two different ways. The first refers to the water contained in the pore space that will not flow out of the rock and into the wellbore during production. This volume is accurately determined only by a relative permeability measurement, but can be reasonably estimated from a capillary-pressure saturation curve. This water volume is primarily a property of the rock and the wetting conditions. The second use of BVI refers to the water that is not displaced by hydrocarbons during the filling of the reservoir. This volume is a function of both the capillary-pressure curve for the rock and the height above free water. In a transition zone, this water volume can include water that can be produced. However, for a sufficient height above free water, capillary forces can drive water saturation to levels well below the point at which the relative permeability to water is effectively zero. [1]

The FFI is the free fluid volume and FFI = φ - BVI. In the other expression, the Mean T2 (or SDR) model, the size parameter enters through the geometrical mean of the relaxation spectra, T2gm. [1]

5. Methodology:
The analysis of T2 distributions aimed at proving estimates of the bound-volume irreducible water and permeability. T2 analysis can also be used to calculate porosity, calculate the geometric mean of the distribution, and track the position of the modes (peaks of the distribution).

1) Porosity calculation: The Porosity module calculates porosity for the T2 distribution obtained from the MRIL tool. Figure 2
   a) Set the required input values
   b) Calculate the NMR porosity

2) Estimation of the T2 geometric mean (T2LM):
The T2LM is the geometric mean of the T2 distribution. This parameter is used for calculating the mean pore size and is used in permeability equations. The T2LM is computed by averaging the logarithms of the relaxation times in distributing each weight by its signal amplitude. The T2LM can be calculated for the whole T2 distribution, or part of the T2 distribution, by specifying minimum T2 and maximum T2 values.

3) Calculation of the bound fluid:
The T2 distribution is subdivided on the basis of pore size and fluid type. The shortest relaxation times contain clay and capillary bound water, collectively referred to as the "Bound Fluid Volume" (BFV). The BFV contains both clay and capillary bound water (BFV = BVI + CBW)

Where:
BFV = bound fluid volume
BVI = the capillary bound water
CBW = clay bound water
4) **Estimation of T2 bumps:**
The amplitude of the modes of the T2 distribution has been calculated. Where amplitude is scaled to porosity, then the porosity of the modes of the T2 distribution has been calculated.

5) **Permeability:**
There are three permeability models available for use with NMR data, SDR method has been selected for this research.

**SDR model:** [2]

\[
K = C_1 \cdot T_{2LM}^{a_1} \cdot \phi_{NMR}^{b_1}
\]

Where:
- \( T_{2LM} \) = logarithmic mean T2
- \( \phi_{NMR} \) = NMR porosity (V/V)
- \( C_1, a_1, b_1 \) = coefficients

6) **Tracking the T2 of the modes of the distribution (Peak Tracking):**
It is agreed upon the fact that the Peak Tracking module tracks the position of the peak of a T2 Mode
based on search limits. The peak is spline fitted for accuracy. [4]

6. Results & Discussion:
Figure 3 below represents data from a Limestone formation in Iraqi oil field. The NMR porosity parameters have been set to calculate PHIT & PHIE, the T2LM has been calculated and used in Permeability equation, the T2 multi cutoff, saddle point and spectral analysis also calculated to find BVI, FFI and CBW.

Track 1 contains gamma ray and calliper logs. Track 3 shows the NMR permeability using SDR equation (green curve), the SDR model will give good estimates of permeability when the porosity is unaffected by HC.

Track 5 contains NMR porosity PHIT & PHIE (Black curve) further BVI, FFI and CBW. The NMR interpretation results show the logs through a good-porosity (PHIT= 0.15-0.23 and PHIE= 0.10 -0.20), and the permeability ranged (200-850 md).

NMR porosity is Lithology- independent, the change from Limestone in displayed log to Shale has no effect on the accuracy of porosity values. In addition, a comparison with core porosity has been made and it has been found that there is a slight difference between the NMR porosity and core Porosity, for example at depth 3864 m the core porosity was 0.17 while the NMR porosity was 0.20, and at depth 3916 the core porosity was 0.05 and NMR porosity was 0.08 and that because of shale existence (see the Gama log).

Over the depicted interval, the log shows the almost clean Limestone formation, and an intervening shale between the Limestone layers and at the bottom. The zone of oil has been detected between depth (3835-3910) meter furthermore clay bound water, irreducible water, and free fluid, the oil – water contact can be easily identified by using resistivity logs at depth 3915 m.

7. Conclusions:
1. NMR is the most advanced and effected way for formation evaluation which provides an accurate calculation of Petrophysical properties.
2. The NMR represents an advanced tool for petrophysicist to determine as much as possible data during interpretation.
3. NMR is a significant way to calculate the porosity and permeability, further the water volume in reservoir and transition zone.
4. The NMR cost is an effective tool because a reduction in the number of traditional Wireline has been run to get same information.
5. NMR permeability, clay bound water and detection of free fluid zone is the core of this tool, therefore; applying the NMR will be a useful tool for petrophysicist and reservoir engineer to get required information and to achieve their plan.

8. References:
[1] George R C, Lizhi Xiao and Manfred G P 1999 NMR Logging Principles and Applications, Halliburton Energy Services (Halliburton Energy Services Publication, USA) p 251.
[2] NMR interpretation Manual (Paradigm TM Geophysical) 2013 chapter 1, 6 and 7
[3] Robert Freedman 2006 Advances in NMR Logging JPT (Schlumberger Oilfield Services)
[4] Robert Freedman1 and Heaton1 N 2004 Fluid Characterization using Nuclear Magnetic Resonance Logging 45 241–250
Figure 3. Well log data including NMR