Magnetic resonance relaxation measurements using open-geometry sensors to assess the clog state of constructed wetlands

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Abstract

Monitoring the T_1 relaxation of wetland clog matter has previously been identified as a gauge of its clogged state [1]. Magnetic resonance (MR) sensors explored in other work have typically been of a bore-whole configuration, which may not be ideal in a wetland environment where the sensitive volume of the sensor may become physically clogged and therefore inoperable. This work investigates two open-geometry sensor designs and a short study is presented to determine the suitability of the sensors for monitoring the clog state of wetlands. It was shown that a bar magnet geometry has a higher stray field than that of the four magnet surface sensor also presented, leading to a prohibitively short T_2^{eff}. This means that the T_1 values collected are notably shorter and not useful for distinguishing between clog state for the single magnet sensor. By contrast the four magnet surface sensor has a longer T_2^{eff}, making it more suitable for T_1 measurements; where $T_1 = 915 \pm 212$ ms for a very thinly clogged sample, and $T_1 = 127 \pm 27$ ms for a heavily clogged sample. This offers a clearly resolvable difference in the T_1 values allowing the clogging state to be easily determined and making this sensor the desirable choice for long-term embedding.

Keywords

Constructed wetland, magnetic resonance, surface sensor, clogging, spin lattice relaxation

1. Introduction

While original predictions for the lifetimes of constructed wetlands for wastewater treatment was on the order of 50-100 years, it is been observed that refurbishment after as little as a decade is far more common [2]. This occurs when the gravel matrix of the wetland becomes clogged with material, preventing efficient water treatment. Wetland re-conditioning is a costly process, and means that the wetland will be unable to perform water treatment during the refurbishment, which is not ideal for the operator. The ability to monitor the clogging state may allow the wetland operator to better manage reed beds and intervene in a timely manner if a bed becomes clogged.

Clog state is a measure of pore occlusion, and in a laboratory setting magnetic resonance techniques have been proven to be able to successfully identify clog state through both T_1 and T_2^{eff} measurements [1, 3-4]. Previous sensors have been of a Helmholtz-style magnet configuration, with a single solenoid used for RF transmit and receive. This geometry is non-ideal for long term embedding into a reed bed as the sensitive volume of an enclosed solenoid could easily become clogged with gravel making it inoperable.

A unilateral MR sensor would be a powerful tool for measuring and analysing the clogging state of a constructed wetland. Existing work has seen embedded unilateral sensors used for a variety of applications, such as the monitoring of concrete [5]. There are a number of unilateral MR sensor designs that are potentially viable for wetland analysis, including a horseshoe arrangement (like the commercially available NMR MOUSE [6]), a Schlumberger-style magnet arrangement [7], or a surface GARField [8]. When considering a magnet arrangement for wetland investigation there are various considerations to be addressed. Foremost the sensitivity to the clog state of the sensor is vital, as determining clog state is the ultimate intended use of the device and an increased sensitivity allows for an easier classification of the overall health of the wetland. The size of the volume investigated by the sensor is also important; macroscopic variations in the state of the reed bed may yield unrepresentative results depending on where the sensor is placed if the investigated volume is too small, however this problem can be partially mitigated by using multiple sensors. Given the size of the investigated region compared to the size of the actual reed bed the sample geometry itself is unimportant. Sensor cost also factors into the choice of sensor. While it is possible to construct very elaborate magnet arrangements, with well-matched sets of magnets, this can become costly which is not ideal for a sensor intend to be embedded long term into a wetland module. Reduced costs can also facilitate the possibility of embedding multiple sensors into each wetland, which is desirable for better determination of the wetlands health. Finally, the signal-to-noise ratio (SNR) when interrogating wetland samples must be considered.

While a number of unilateral systems where investigated for this application, two designs were taken forward due to their favourable signal-to-noise ratio (SNR) when scanning very thinly clogged wetland samples. The authors recognise that additional work on other magnet arrangements may have led to an improved signal-to-noise ratio and that the designs chosen may not have been the theoretically optimal arrangement. A computer simulation of the surface GARField provided a very large and homogeneous sensitive region in simulations, however gave unfavourable results when prototypes were constructed.

This work presents two unilateral MR sensor designs for the explicit intention of embedding in a wetland for long-term monitoring of the clog state. The first sensor used the stray field of a simple bar magnet, a design well documented in the literature [5, 9]. The second sensor utilised the stray field of a four magnet arrangement. The geometry was similar to the arrangement used by Hills *et al.* for their low cost Halbach array [10]. The stray field at the surface of the sensor was then used for MR detection similar to work by Chang *et al.* [11]. To the authors knowledge this exact design has not previously used by other groups and has only been presented in earlier work [12, 13]. The general differences between the two sensor designs are their operating field strength (B_0), the field homogeneity in the direction of the field, and the orientation of the field B_0 with respect to the face of the magnet(s).

It is important to note that temperature has a major effect on the strength of permanent magnets [14]. Therefore when embedded, seasonal temperature variations experienced will have an effect on the collected MR signal from a clog sensor. Temperature considerations will not be addressed in this work, however have previously been discussed elsewhere for the four magnet surface sensor [13].

This study was part of a larger venture to develop an automated constructed wetland module as part of an EU FP7 project - ARBI. For a fully automated wetland module knowledge of the clogging state is critical to adequately optimise other parameters, such as aeration and heating.

2. Methods and Materials

2.1 Four magnet surface sensor

The stray magnetic field from an array of four magnets was used to generate a region of uniform field for MR detection. The magnet arrangement was built using four 30 x 40 x 40 mm^3 N42 neodymium magnets (First4Magnets, Tuxford, UK) polarised along the 30 mm axis. The four magnets were arranged as shown in Fig. 1(a). There was a 30 x 40 mm^2 gap between the magnets where a region of uniform magnetic field existed. This was in agreement with computer models (Ansoft Maxwell 3D, Ansoft Corporation, Pennsylvania, USA) as shown in Fig. 1(b). The computer simulation was conducted for the region just above the magnets and RF coil.

Five 1.5 mm thick steel plates were added under the four magnets to reduce the overall field gradient in accordance with computer simulations; this was ultimately 1.6 T/m in the direction of B_0 (see Fig. 1(a)). Copper tape was placed over the magnets to reduce excessive RF loading of the magnets.

Radio Frequency transmission and detection was conducted slightly above the magnet surface with a with a simple two-turn loop surface coil [15]. The coil was wound with 0.5 mm enamelled copper wire (Rowan Cable, Hertfordshire, UK) and attached to a parallel-series tuning board. Fixed ceramic (1680 pF tuning, 390 pF matching) capacitors and two 12 -100 pF variable capacitors (Johanson Manufacturing, New Jersey, USA) were used to achieve resonance at the desired frequency of 10.3 MHz. The frequency of 10.3 MHz was chosen as this was the field strength atop the magnets arrangement; this provided the most homogeneous region above the magnets and also allowed for the highest MR signal due to the higher field strength.

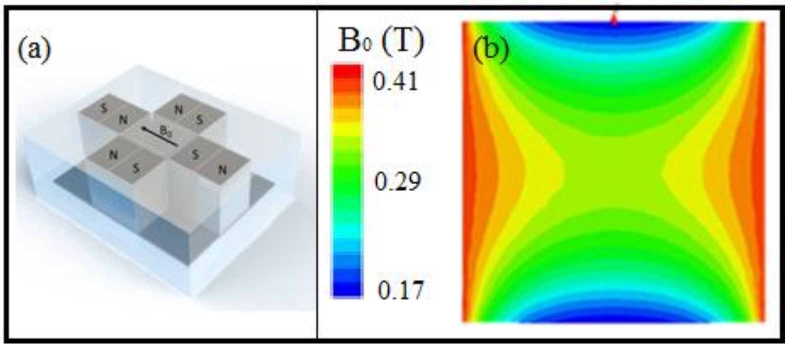

Fig. 1: (**a**) Schematic of the four magnet unilateral surface sensor. A uniform magnetic field is generated in the magnet gap. A two-turn surface coil is used for RF transmission and receiving. (**b**) A computer simulation of the magnetic field over the surface of the magnets. The colour bar is to help illustrate the field homogeneity, and does not represent true magnetic field values.

2.2 Bar magnet sensor

A single cylindrical magnet, acting like a traditional bar magnet is the simplest magnet arrangement to generate a uniform magnet field for unilateral MR measurements [9]. For this arrangement two large cylindrical magnets (height = 20 mm, radius = 35 mm: Magnet Monster, Flensburg, Germany) where held together under their own magnetic force to generate a strong uniform magnetic field (Fig. 2(a)); approximately 0.5 T at the surface of the magnet. As with the four magnet surface sensor, copper tape was placed over the magnet to reduce RF loading of the magnets.

A figure 8 RF coil (25 x 20 mm^2) was employed on this design and attached to a similar tuning board to that described previously, with two 12 -100 pF variable capacitors (Johanson

Manufacturing, New Jersey, USA), and 830 pF fixed ceramic capacitors (MultiComp Corporation, Leeds, UK) for tuning. This gave a resonance at 17.7 MHz, appropriate for the 0.41 T field in the sensitive region of the RF coil. In the direction of the magnetic field B_0, the field gradient was 11 T/m.

A magnetic field map for this magnet was taken using a simple magnetic field plotter built from a 3-axis machine (Part # 5-300/301; Milford Instruments Ltd, Leeds, UK) and a GM08 guassmeter (Hirst Magnetic Instruments Ltd., Falmouth, UK). The machine was re-calibrated after each line of readings. Four readings were taken at each point to ensure reliability (Fig. 2(c)).

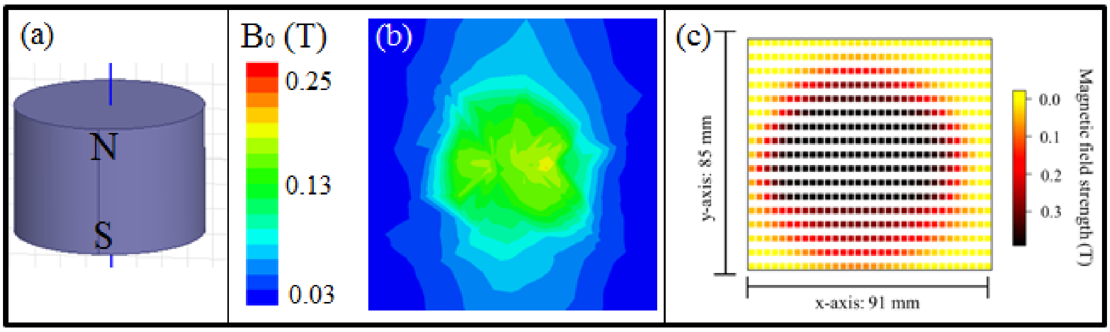

Fig. 2: (**a**) Schematic of the bar-magnet unilateral surface sensor. A uniform magnetic field is generated above the magnet. A single-turn butterfly coil is used for RF transmission and receiving. (**b**) A computer simulation of the magnetic field over the surface of the magnet. The colour bar is to help illustrate the field homogeneity, and does not represent true magnetic field values. (**c**) A magnetic field map for the field 5 mm above the magnet surface.

2.3 MR protocol

The signal generation and collection was undertaken using a Kea 2 spectrometer (Magritek, Wellington, New Zealand), run on the Prospa 3.12 software. Two pulse sequences were employed in this study. T_2^{eff} measurements were acquired using a Carr Purcell Meiboom Gill (CPMG) [16] sequence. A value for T_2^{eff} was then obtained by fitting a mono-exponential curve to the echo integrals in Igor Pro v6.3 (WaveMatrics, Oregon, USA).

T_1 measurements were recorded by taking trains of CPMG echoes with different experimental repetition times. Echo integrals were summed to increase the overall signal strength and therefore reduce the required number of averages. As with T_2^{eff} measurements, summed echo integrals were fitted with a mono-exponential curve in Igor Pro v6.3 (WaveMatrics, Oregon, USA).

2.4 Sample preparation

NMR experiments were carried out on two wetland samples; referred to later in this work as ‘Thick’ and ‘Thin’. The thick sample was provided by ARM limited (Rugeley, UK) and is representative of a heavily clogged wetland. The thin sample was taken from the constructed wetland prototype built at Nottingham Trent University. At the time that the sample was collected, this was little more than water and gravel and would be representative of a newly commissioned wetland.

Samples were stored in 60 ml cylindrical polypropylene bottles with a wall thickness of approximately 1 mm. Samples were placed horizontally, directly against the surface of the transmit-receive coil during MR experiments.

3. Results and discussion

3.1 T_2^{eff} measurements

Initially T_2^{eff} measurements were taken with both sensors. Parameters were optimised to achieve the best echo train for the sensor in question. Fig. 3(a) shows T_2^{eff} measurements for each sensor on a thin sample. T_2^{eff} for the bar-magnet sensor is very short, only 309 ± 60 µs compared to 32.4 ± 13.7 ms with the four magnet surface sensor (a factor of 100 difference).

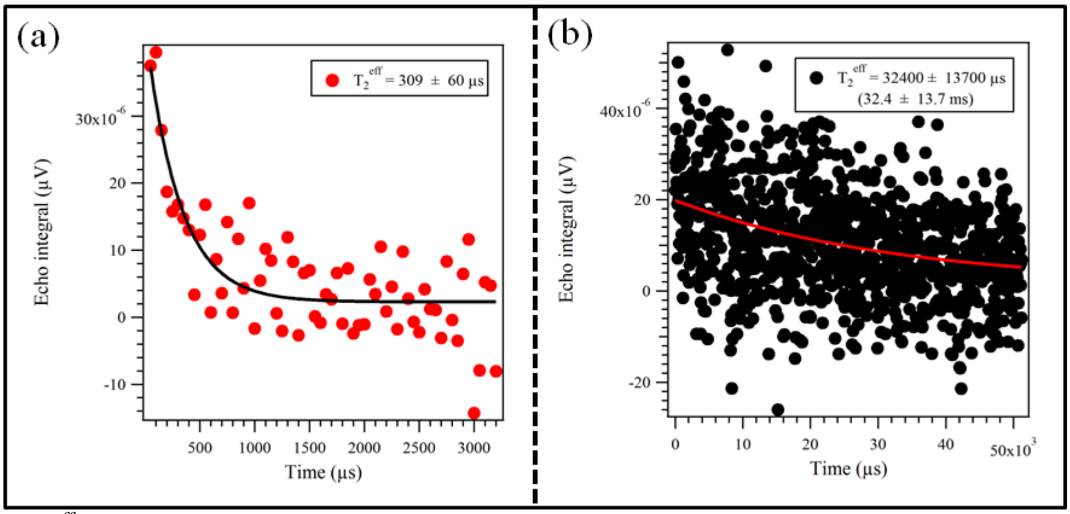

Fig. 3: T_2^{eff} measurement taken using a CPMG sequence; τ_E = 50 µs, 2048 scans on the thin sample. (**a**) Bar magnet style sensor, 64 echoes. (**b**) Four magnet surface sensor, 1024 echoes. T_2^{eff} values were extracted from the fittings, they are displayed along with their associated fitting parameter errors.

It is apparent from Fig. 3 that the SNR when taking measurements on thin wetland samples for both sensors is poor, however it was still superior to other designs explored as part of this study. This was in part due to the unfavourably noisy conditions in the laboratory environment, which would be less of a problem when embedded in a wetland module away from many electronic devices. It is observable from Fig. 3 that T_2^{eff} measurements would provide an unsuitable gauge of clog state with the presented sensors due to the poor SNR. Summing echoes from the CPMG train for a single data point gives a far superior signal intensity for the same number of scans, which is satisfactory for T_1 measurements.

Such a short T_2^{eff} measurement using the bar-magnet sensor was due predominantly to field inhomogeneity in B_0, where the gradient was 11 T/m. This was a factor of 7 greater than the gradient in B_0 for the four magnet surface sensor, that was 1.6 T/m. In accordance to theory [17] the signal decay due to dephasing was proportional to the square of the field gradient if other factors were the same. While this was not strictly the case for the systems presented, the field gradient difference means that there should be a dissimilarity in T_2^{eff} value collected of a factor of 49; this was only a factor of two different to the difference observed in T_2^{eff}, showing it to be the dominant effect.

3.2 T_1 measurements

T_1 measurements were recorded, as described earlier, for both sensors on both samples and are displayed in Fig. 4. Only a small difference can be seen between the vastly different samples on the bar-magnet sensor. In addition, the thick sample has a marginally longer T_1 time than the thin sample, which does not support earlier work [1, 2, 12] or the findings on the four magnet surface sensor. This implies that the bar magnet sensor is insensitive to clogging state making it unsuitable for wetland study. This T_1 insensitivity is due to the relationship between T_1 and T_2^{eff} in systems such as this, limiting the maximum T_1 value.

T_1 measurements collected using the four magnet surface sensor show significant differences between the samples, by virtue of its longer T_2^{eff}. T_1 is calculated to be 127 ± 27 ms for a heavily clogged sample and significantly longer at 915 ± 212 ms for the thinly clogged sample.

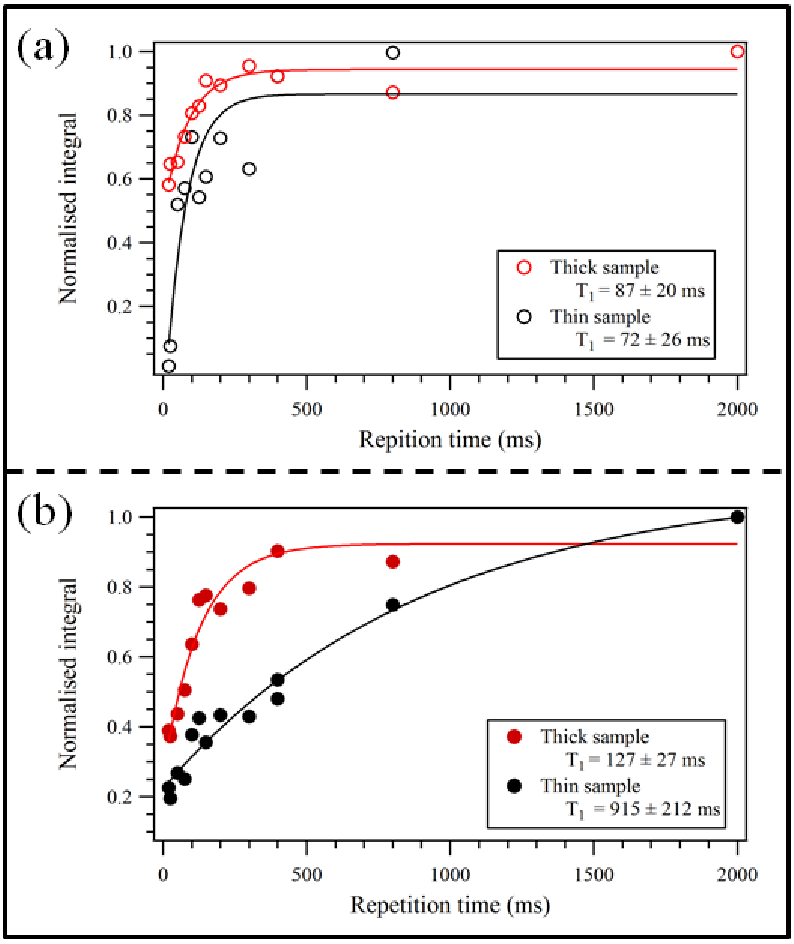

Fig. 4: T_1 measurement taken using multiple CPMG sequence with different repetition times; 2048 scans on the two different samples. (**a**) Bar magnet style sensor, 16 echoes summed, τ_E = 50 µs. (**b**) Four magnet surface sensor, 64 echoes summed, τ_E = 100 µs. T_1 values were extracted from the fittings, they are displayed along with their associated fitting parameter errors.

4. Conclusions

Two functional unilateral MR sensors have been presented in this work and their use for assessing the clog state of a constructed wetland environment has been assessed. The prohibitively short T_2^{eff} for the bar-magnet style sensor (T_2^{eff} = 309 ± 60 µs), limits the T_1 measurements, with T_1 = 87 ± 20 ms for the thick sample and T_1 = 72 ± 26 ms for the thin sample. The minimal difference between the T_1 values shows an insensitivity to the clog state.

The four magnet surface sensor has a T_2^{eff} that is a factor of one-hundred longer (T_2^{eff} = 32.4 ms) due to an improved field homogeneity in B_0, and as a result the T_1 values show a significant difference for the two samples, with T_1 = 127 ± 27 ms for the thick sample and T_1 = 915 ± 212 ms for the thin sample. This makes the four magnet surface sensor a suitable choice for testing in wetland.

Further work of interest would be to test the four magnet arrangement in a functional wetland. Preliminary experiments have identified an issue when water-tightening the sensor, as even a small additional layer of material removes from the sensitive volume of the coil. Continuing investigations will study a new water-tightening technique coupled with improved electronics. Ultimately a long-term study of clogging in a wetland using MR techniques and an embedded unilateral sensor is desired.

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