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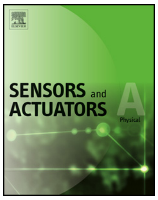

Temperature dependence of magnetic resonance probes for use as embedded sensors in constructed wetlands

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ABSTRACT

Constructed wetlands are now accepted as an environmentally friendly means of wastewater treatment however, their effectiveness can be limited by excessive clogging of the pores within the gravel matrix, making this an important parameter to monitor. It has previously been shown that the clog state can be characterised using magnetic resonance (MR) relaxation parameters with permanent magnet based sensors. One challenge with taking MR measurements over a time scale on the order of years is that seasonal temperature fluctuations will alter both the way that the sensor operates as well as the relaxation times recorded. Without an understanding of how the sensor will behave under different temperature conditions, meaningful information about the clog state cannot be successfully extracted from a wetland. This work reports the effect of temperature on a permanent magnet based MR sensor to determine if the received signal intensity is significantly compromised as a result of large temperature changes, and whether meaningful relaxation data can be extracted over the temperature range of interest. To do this, the central magnetic field of the sensor was monitored as a function of temperature, showing an expected linear relationship. Signal intensity was measured over a range of temperatures (5 °C to 44 °C) for which deterioration at high and low temperatures compared to room temperature was observed. The sensor was still operable at the extremes of this range and the reason for the signal loss has been studied and explained. Spin-lattice relaxation time measurements using the sensor at different temperatures have also been taken on a water sample and seem to agree with literature values. Further to this, measurements have been taken in an operational wetland over the course of 203 days and have shown a linear dependence with temperature as would be expected. This work concluded that the sensor can perform the task of measuring the spin-lattice relaxation time over the required temperature range making it suitable for long-term application in constructed wetlands.

1. Introduction

Constructed wetland (CW) technology began to proliferate heavily in Europe during the 1980s and 90s, as well as in North America, and now is a commonly employed method for water treatment in both regions, as well as in China where the CW has gained increasing interest since the late 1990s [1,2]. A CW comprises of an aggregate matrix, typically gravel, through which the wastewater is mechanically filtered and where microorganisms grow. Over time a build-up of particulate and excessive biofilm growth occludes the pores preventing successful transfer of the wastewater through the bed. Eventually a critical point is reached where the bed can no longer treat wastewater and floods, typically after a decade [3]. Reconditioning of a wetland after it has become critically clogged is a time consuming and expensive process, and should therefore be avoided if possible. As a result, it is important to monitor the clogging level of systems to allow for optimal treatment efficiency. Ascertaining the clog state is also a useful research tool when examining wetland operation and design.

A number of methods exist to characterize the clog state in the literature and these fall into three general categories, the measurement of hydraulic conductivity [4], determining the hydrodynamics of the system on a larger scale using tracer dyes (such as Rhodamine WT) [5,6], or by determining the quantity of solids present within the pores by drying out a wetland sample [7]. Each of these techniques have their own strengths and weaknesses, and

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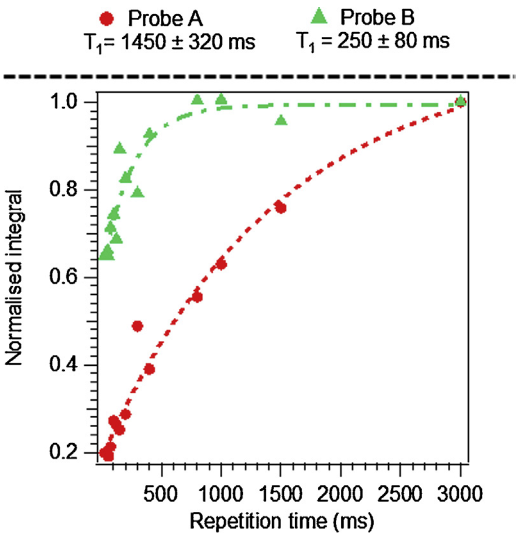

Fig. 1. Example T_1 relaxation data taken from two probes embedded in established constructed wetlands.

this has been well covered by others [8]. One limitation for all of these methods is that they cannot be automated and require human input either in extracting a sample and analyzing it in a laboratory, or running experiments on site. This ultimately makes taking the measurements costly over the lifetime of a wetland or research study when labor is considered.

An alternative to these methods is by using pulsed (time domain) magnetic resonance (MR) sensors. MR works by a careful manipulation of the magnetic moments of certain nuclei, including the hydrogen in water molecules, using radio frequency (RF) pulses. These typically determine parameters called relaxation times, T_1, or spin-lattice relaxation and T_2, or spin–spin relaxation; although another parameter T_2^{eff} is more commonly measured than T_2 with this type of sensor owing to the inherent field inhomogeneity. Sensors like this have found a disparate range of applications in recent years partly due to the reducing cost of micro-electronics [9].

Determining the clog state of both model systems and wetland samples have been extensively investigated in the laboratory setting using relaxation measurements [10–14]. The parameter T_2^{eff} has been previously used to successfully characterize clogging in a model system where a highly homogeneous magnetic field has been used for MR measurements [11,12], however this was not possible with the inhomogeneous magnetic field of a low-cost permanent magnet system such as the type used in this work [14]. Therefore this work focusses on T_1 relaxation measurements which have also been used to determine the clog state with a similar sensor in the past [10,13,14].

Further investigation has seen a series of MR sensors constructed and permanently embedded into the gravel matrix of a constructed wetland for long term monitoring of the clog state, proving that the sensors can successfully operate in a functioning wetland. To validate their operation over these time scales, selected probes have been extracted and re-tested on known samples in the laboratory environment after a number of months: The only observed change to the sensors was discoloration of the plastic housing of the probes. Fig. 1 shows some example data taken from two probes embedded in mature, operational wetlands (operated by ARM Ltd., Rugeley, UK).

Probe A represents a probe in a well-established operational bed, while probe B was in a different bed in a location where significant clogging was believed to be present. There is a factor of ~6 difference between these two values showing a great sensitivity to clog state. This difference would be greater when investigating a newly commissioned bed compared to one that was critically clogged, which would represent the extreme ends of potential clogging scenarios. While useful to validate the technique, there are additional considerations when monitoring an operational wetland over long time scales.

An important consideration is temperature. While a constructed wetland's water temperature is not necessarily the same as the air local temperature [15], seasonal variation will mean that a constructed wetland will be subject to a range of temperatures which depends on location. In order to better validate the sensor technology, the effect of temperature on the operation of the physical sensor and how temperature may affect the sample explored must therefore be understood.

MR measurements are sensitive to the temperature of the sample under test. Temperature is known to heavily affect spin-lattice (T_1) relaxation times in water [16–18], with a strong linear relationship between the T_1 times and temperature observed between the boiling and freezing points of water. This holds true for the range of temperatures that would typically be encountered by a device left outside (−5 °C to 40 °C) although it should be noted that it is not possible to obtain a signal from water below freezing. This relationship is well understood and has led to the development of MR thermometry [19–21].

Within an unclogged wetland, the majority of the bed will be free water and aggregate. In the case of a typical aggregate such as gravel only the free water would be detectable by the MR probe, hence T_1 values recorded in an unclogged wetland would be expected to vary with temperature in the same way that it does for water. Clogging occurs within the wetland due to a build-up of sediment and the growth of biofilms, both of which are useful to the treatment of water in the correct quantity. In a clogged wetland these other components representing water with high concentrations of particulate in it, or water comprising biofilms would be detectable by the MR probe [13]. The relaxation times of these components (i.e. particulate associated water and water in biofilm) might not be affected by temperature in the same way as water, however these components are known to have shorter relaxation times than water, so the influence on a final T_1 relaxation time would likely be less significant than the effect of free water. Additionally the root and rhizome network of the aquatic plants growing within the wetland would also be measureable by the MR sensor, however there should be no other materials or pollutants within normal domestic wastewater that would significantly alter the recorded T_1 value. This is not necessarily the case for all wastewater types such as those containing large quantities of hydrocarbons although these are not considered in this work.

The physical effects that temperature has on the sensor must also be considered, as temperature changes are known to effect the magnetic field strength of permanent magnets [22]. In this work we use a 'Helmholtz-style' sensor (shown in Fig. 2) and sensors of a similar design to this have been presented elsewhere [10]. A probe of a comparable design was used to collect a set of preliminary measurements exploring the temperature effects [23] however the design and construction technique has been refined since then. This design used two NbFeB magnets to generate a field in the magnet gap where a six-turn solenoid was placed for the transmission and reception of RF signals. Steel disks were used on each magnet to reduce the magnetic field inhomogeneity however, the magnetic field gradient was still very large. This made the collection of a free induction decay (FID) impossible and rendered many magnetic resonance techniques ineffectual. As a result, signal must always be obtained by collecting an echo [24].

With regards to the constituent magnets of the sensors, a variety of widely available magnet types were considered including ceramic, samarium-cobalt (SmCo) or neodymium-iron-boron magnets (NdFeB). The literature shows that both SmCo and NdFeB have