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Advances in Multiphase Flow Measurements Using Magnetic Resonance Relaxometry

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ABSTRACT. When it comes to the measurement of bitumen and water content as they are produced from thermally exploited reservoirs (cyclic steam stimulation or steam assisted gravity drainage) most of the current tools that are available in the market fail. This was demonstrated previously when our group introduced the first concept of a magnetic resonance based water-cut meter.

The use of magnetic resonance as a potential tool for fluid cut metering from thermally produced heavy oil and bitumen reservoirs is revisited. At first a review of the work to date is presented. Our recent approach in the tackling of this problem follows. A patented process is coupled with a patented pipe design that can be used inside a magnetic field and can capture fluids up to 260°C and 4.2MPa. The paper describes the technical advances to this goal and offers a first glimpse of field data from an actual thermal facility for bitumen production. The paper also addresses an approach for converting the current discrete measurement device into a continuous measurement system. Preliminary results for this new concept are also presented.

1. INTRODUCTION

Low field NMR relaxometry is a technology that offers significant benefits in reservoir characterization through the so-called magnetic-resonance logging tools that are offered by the oil and gas service companies (Coates et al., 1999). These tools can offer measurements of porosity, permeability, mobile and bound fluids and potentially saturations, if they are properly calibrated. Recently, the service tools also provide information about fluid viscosity and other fluid properties, again after careful calibration of the tools. These calibrations can be done through measurements in bench-top systems that perform the same measurements at much higher signal-to-noise ratio.

Over the past ten years the Tomographic Imaging and Porous Media (TIPM) Laboratory has focused on research, development and commercialization of low field NMR technology. Although the interest was primarily in heavy oil and oil sands applications, some technology advancements apply to conventional oils as well. Initially, much of the work has centred on core analysis. However, since it was realized that NMR could be used for determination of fluid content in cores, the jump to measurement of fluid content in fluid streams was natural. Fluid characterization in conventional oil and gas reservoirs can be done with a multitude of logging techniques including magnetic resonance. The term magnetic resonance induced fluid typing is used nowadays from the service companies to tackle this problem.

The fluid stream characterization work in our laboratory aimed at several potential applications, with original targets in heavy oil and oil sands. First the work was directed in the determination of fluid content in oil sand process plants that process oil sand mining ore and froth (Kantzas, 2004). The work was then extended to measurement of water cuts in oil/water streams (Mirotchnick et al., 2003, 2004). This was followed by work in the determination of fluid viscosities both in bulk streams, emulsions and in-situ (Bryan et al., 2005). Finally the research dealt with the measurement of fluid content, viscosity and mass transfer properties of heavy oil and bitumen mixtures with solvents (Goodarzi et al., 2007; Wen and Kantzas, 2004).
In co-operation with Canadian Natural Resources Limited (CNRL) a water-cut meter utilizing low field NMR technology was operated for approximately eight years on two different cyclic steam injection heavy oil well pads (Allsopp et al., 2001; Wright et al., 2004). The only other recently published technology that tries to measure fluid production at thermal conditions is the nuclear fraction metering technology offered by Schlumberger. This technology consists of the combination of a venturi meter and a gamma-ray source. It was field tested for a few hours in a SAGD operation in Western Canada (Hompoth et al., 2008a, 2008b). The technology shows promise but it cannot reach the specified temperature conditions imposed to us by the client operating companies.

2. PHYSICAL PRINCIPLES

The principle of proton NMR deals with the response of hydrogen bearing molecules to a sequence of magnetic field pulses. As the protons in hydrogen bearing molecules are exposed to a magnetic field they acquire energy. When the magnetic field stops the protons return to their (random) original state and emit this energy back to the environment. The released energy is recorded and amplified through specific hardware. This energy is detected as a decay curve that is then fitted to a multi-exponential spectrum of characteristic transverse relaxation times ($T_2$). The detailed physics of magnetic resonance can be found in numerous literature sources.

Figure 1 shows a spectrum of a heavy oil / water emulsion. This spectrum is typical of the types of spectra encountered in the analysis of NMR extracted fluid data. It is, therefore, used as an example to explain how the NMR analysis is done.

Fig. 1  Representative emulsion NMR spectrum indicating heavy oil and water peaks(from Kantzas, 2004)

The x-axis denotes the relaxation times $T_2$ and the amplitude denotes the signal strength at each relaxation time. The dashed vertical line indicates the characteristic cut-off point that is used to separate heavy oil signal from water signal and is based on theoretical and empirical considerations. In this case the slower relaxation is attributed to water and the faster relaxation is attributed to heavy oil. This interpretation was possible after numerous spectra of pure substances were collected. The smaller peaks between the dominant oil and water peaks are attributed to water droplets present in an emulsified state.

The information used for analysis of the NMR spectra often includes a weight or volume measurement, and calibration standards for comparison to the measured spectra. The properties of the spectra that are very useful are the amplitude ($A$) of the full spectrum or a part of the spectrum that corresponds to a given phase, the location of the spectra peaks as indicated by the relaxation time $T_2$, or in the case of complex spectra a characteristic average relaxation time. The most commonly used relaxation time for averaging purposes is the geometric mean relaxation time, $T_{2gm}$ that is defined as:
A spectrum contains significant information that is qualitative until the amplitude is translated into a mass or volume number in which case the spectrum information becomes quantitative. In order to reach this point, we require calibrations that will offer the amplitude that corresponds to a unit volume or a unit mass. For most of our applications the amplitude per unit mass is defined through the amplitude index (AI) as follows:

\[ AI = \frac{A}{m} \]  

(2)

As a result, if one knows the amplitude and amplitude index of a given compound, NMR spectra will be helpful to provide the actual amount of this compound as soon as we identify it in the spectrum. In many studies, instead of AI, it is customary to use another variable called the relative hydrogen index (RHI) that is defined as the ratio of AI values of a specific compound to that of water:

\[ RHI = \frac{AI}{AI_w} \]  

(3)

Both AI and RHI have a sound scientific basis as they are related directly to the density of hydrogen atoms in the fluid. In practical applications they may be thought of as calibrations. The main difference is that AI values are instrument specific, but RHI values should be instrument independent and only depend on the composition of the stream at hand.

With respect to fluid analysis, the only parameter that will distort the NMR spectrum unexpectedly will be the presence of paramagnetic ions (such as iron or rust). Parameters that play havoc with conventional sensors such as salinity of brines and emulsion inversions are completely indifferent to NMR.

Temperature is an important factor that will shift the NMR peak locations of different fluids. Thus when measurements are made it is required that the temperature remains constant. Calibrations are then made to compare spectra at different temperatures to corresponding standards, and corrections are made to the predictive algorithms for fluid content and fluid property determination.

Before providing predictive equations for different circumstances, let us consider some relaxation times for different fluids. At room temperature bulk water relaxes at approximately 2300 ms whereas bitumen will relax with a \( T_2 \) of less than 10 ms.

In general, the more restricted the hydrogen bearing molecule, the faster its relaxation time. Restrictions to a molecule can occur either through an increase in viscosity, or through the confinement in small spaces (such as pores).

When dealing with emulsions of heavy oil or bitumen and water, it is often assumed that the \( T_2 \) of bitumen does not change much when the bitumen is emulsified because it is already quite fast, but the \( T_2 \) of water changes significantly when it is emulsified. This is taken into account when interpreting the spectra to conclude if we have a separated flow, oil in water or water in oil emulsion by the strong impact the location of the water signal has on the geometric mean of the spectra.

3. LABORATORY DATA
The first and most heavily studied NMR metering application was that of a two-phase (water-oil) compositional meter. Based on equation (2), if the total weight (or volume) of a sample is known, then given a constraint (or cut-off) for the separation of the two fluids, one can predict
the water and oil cuts. In a simplified approach this can be done through:

\[ \%W_c = \frac{A_w}{A_w + A_o (RHI)} \]  

(4)

The cut-off approach separates the spectrum in two components, one corresponding to oil and one to water.

Fig. 2 shows some early laboratory results. The correlation between NMR results and Dean-Stark results is approximately 99%. Although it was not expected to achieve such precise results in the uncontrolled field environment, it was considered encouraging enough for field applications.

![Correlation for water content prediction in water-bitumen emulsions](image)

Fig. 2 Laboratory data for water-cut determination in water / oil streams (Allsopp et al., 2001)

The combination of equations (2) and (4) can be manipulated to provide the composition of a water / oil / gas stream. In this case the results can be plotted either for individual phases or in a ternary plot as it can be seen from Fig. 3 and Fig. 4 respectively.

![Correlation for water content predictions from NMR and mass balance](image)

Fig. 3 Comparison of water content predictions from NMR and mass balance for mixtures of 2150 mPas oil with brine for a three-phase system (Kantzas, 2004)
The next important development in fluid characterization was the determination of viscosity on-line. The results of this work have been extensively published (e.g. Bryan et al., 2005). It was found that NMR could predict viscosities of single fluids and emulsions with reasonable accuracy without tuning and with excellent accuracy if the algorithm is tuned to specific oils rather than the original generic approach.

The predictive models for viscosity measurements are of the form:

$$\mu = \frac{\alpha}{(RHI)^{\beta} T_{2_{gw}}}$$  \hspace{1cm} (5)

The coefficients $\alpha$ and $\beta$ vary with different systems and depending on whether the model is tuned or not to a specific reservoir.

Fig. 5 show the results of the predictive algorithm for viscosity measurements as it was applied in a wide variety of oils at different temperatures. For this model $\alpha=1.15$ and $\beta=4.55$.

In a parallel project, the value of NMR technology was investigated for bitumen-solvent mixtures. For processes like vapour extraction (VAPEX), it is anticipated that the operator would like to know the bitumen content and produced fluid viscosity for the evaluation of the performance of VAPEX. To this end laboratory work focused on using liquid solvents (both paraffin and cyclic based).
Hundreds of mixtures of oils and solvents were created in different solvent to oil ratios. The NMR spectra were obtained over time and their trends were observed. Several predictive algorithms were designed that are tuned to different solvent / oil pairs. Fig. 7 shows a typical example of these plots that can be used for bitumen content determination from NMR derived parameters.

![Graph showing NMR spectra properties with solvent addition](image)

Fig. 6 Changes in NMR spectra properties with solvent addition (Wen and Kantzas, 2005)

It must be noted that the applications for NMR technology are numerous but only the water-cut metering technology has been field-tested to date. The specifics for field-testing and some preliminary results are discussed next.

4. SENSOR DESIGN

In order to apply the theoretical models for the creation of a field sensor, the standard laboratory designs to date were used as a starting point.

The sensor part consists of an assembly of permanent magnets and transmitter / receiver coils. The permanent magnets cannot be exposed to temperatures greater than 80°C without being damaged. Thus, we have developed a heat-shielded magnet that overcomes this drawback and at the same time increases the maximum process temperature to 260°C. The sampling pipe/tube itself has to be non-conductive and non-magnetic. Additionally, the pipe/tube also has to be able to handle the design conditions of 260°C at 4.2MPa (600psi) for the process fluid.

One of the most critical steps in the program was to define a set of criteria to use as both a guideline for the program and as a means to determine success or failure.

Based in large part on CNRL’s extensive experience in the field the following criteria were set:

1. The sensor should give clear water-cut readouts in % on a local digital or computer display.
2. There should be no “tweaking” of the instrument by the end of the test.
3. The sensor should be operating to give water cuts consistently without interferences.
4. The apparatus results should be comparable to spun cuts within accuracy better than +/- 5 % of water cut readings.
5. The sensor should give repeatable results on the same sample (with +/- 5 % of the water-cut reading).
6. The sensor results should be comparable to Dean Stark extraction within accuracy of +/- 5 % of water cut reading.

Furthermore the instrument should be fitted with the hardware and software necessary for direct communication with the control system (PLC). The process of sampling and measuring should be automated. The measurement signal should be provided to the PLC by a 4-20 mA DC signal. Signals for measurement timing are passed between the instrument and PLC using 120
VAC on/off digital switches. Any other arrangement desired may also be used, as the proposed apparatus should be completely generic with respect to signals to or from the data logger or control systems. A special cabinet system to contain the instrument, its computer, and associated electronics for communication with the PLC was constructed. This cabinet had to protect the instrument, provide adequate ventilation and protect the environment from the instrument (Class 1, Div 2).

5. FIELD TESTING TO DATE

Example field data collected over a 24-hour period were presented elsewhere (Wright et al., 2004). It was demonstrated that the instrument sees changes in water cut with changes in well. Steady and reproducible results were obtained. It was further demonstrated that the test separator acts as a homogenizing buffer to the production data. Examination of the data shows that the tool is remarkably stable with measurements having a standard deviation of 2.2%.

![Comparison of NMR, Centrifuge, Dean Stark and Current online Tool, Well 1](image)

Fig. 7  Comparison of water cut measured by NMR, Centrifuge, Dean Stark and the current online tool (Wright et al., 2004)

Comparisons of the fit of the data with centrifuge cuts in the field and with subsequent Dean Stark extraction were considered satisfactory, considering the sample actually measured by the instrument is not the same as the sample sent to centrifuge, although it is as close as practically possible.

An attempt was made to compare the performance of the original online tool against NMR water cut measurements and against Dean Stark and centrifuge analysis of grabbed samples. A sample for such a comparison is shown in Fig. 7. The striking thing in this graph is that despite the sampling issues the NMR consistently tracks the discrete samples where as the competing instrument is only in range part of the time and is often reporting a number which is completely wrong. The pattern shown here, where the older tool consistently reports numbers which are different from the actual water cut, is typical of the operation of this well pad and is the major reason that the well pad was originally selected to test the NMR.

The first part of our work demonstrated that NMR based fluid content and fluid measurement technology is now feasible. Properties such as fluid viscosity, solvent content and water-cut can be measured on-line with remarkable accuracy and precision. The components that required intellectual property protection were patented (Mirotchnik et al., 2003, 2004). Additional field-testing will be required prior to full commercialization.

6. DESIGN IMPROVEMENTS AND NEW ALGORITHMS

A new company, Perm Instruments Inc., was created to commercialize patented and patentable technology developed in the Tomographic Imaging and Porous Media (TIPM) Laboratory. There has been a very strong interest by the oil companies that support our program to design a sensor that could measure oil, water, solvent, gas and solids in a flowing stream with immediate application in the heavy oil and oil sand development of Western Canada and at a cost comparable or less to that of three-phase test separators.
Fig. 8 is a simplified version of how the system works today. The fluid that has to be analyzed is conveyed to the sampling location inside the magnet (Fig. 8) where it is exposed to a relatively uniform magnetic field.

Any arbitrary emulsion in the measurement zone will yield a relaxation spectrum, which will compose of a water peak and an oil peak. Since the measurement volume is known we can calculate the amount of water present from the spectrum, normalize it to the measurement volume in the pipe and obtain the water cut. As long as there is no appreciable amount of gas the instrument will work very well as is also shown in Fig. 7, from the published data with Canadian Natural (Wright et al., 2004).

This idea has been implemented in an industrial type machine (MRWCM) that is shown in Fig. 9. The magnet, electronics and other support hardware is enclosed in a pressurized system that allows exposure to explosive environments under the Canadian Standard Association (CSA) Class 1 Div 2 classification. The cabinet and supporting structure have a minimal footprint of 1.5 x 1.5 m².

As mentioned earlier in Section 4, the MRWCM design concept meant that the pipe that conveys the process fluids to the point of measurement needs to be specially designed.
Conventionally, pressure piping are designed as per ASME B31.3, which specifies the design requirements. Since, the pipe also needs to be transparent to a magnetic field and be highly resistive, the only materials that could be practically used were different kinds of plastics. Hence, an unconventional design approach was dictated by the meter, which further required extensive testing to demonstrate the performance of the new pipe. This process has since then been successfully completed with the necessary approvals from ABSA (Alberta Boilers and Safety Authority, which is the regulatory authority for Pressure Vessels and Pressure Piping designed and operated in Alberta). The effort has resulted in a one of a kind pipe design using plastic materials that can operate continuously at 260 °C and 600 psig under the harshest fluid environments typical of the oilfields of Alberta. The detailed design of the pipe is currently being patented.

However, there are two areas of further improvement for this technology; (1) the sample has to be captured, thus there is no continuous monitoring; (2) the instrument is an add-on to the three-phase test separator and not a replacement. The first area is currently being addressed as follows:

The need to capture the sample within the MRWCM for a period of time is due to the fact that hydrogen spins need to reach equilibrium state when more of them are aligned along the direction of the magnetic field than in the opposite direction. The sample then remains within the same magnetic field for at least $T_e$ in order for the relaxation to be captured.

The complex population of spins that exist in hydrogen bearing molecules and are excited by the magnetic field of the MRWCM approaches equilibrium state after $T_{eq} \approx 5T$. Then the total time needed for the measurement procedure will reach $T_{meas} \approx 5T_1 + T_2 \approx 6T_1$. For bulk water with relaxation times close to $T_1 \approx 2.5$ sec, the above formula gives $T_{meas} \approx 15$ sec.

With the current size of the uniform magnetic field area of about 10 cm along the axis of the pipe the flow speed is limited to not more than 10 cm / 15 sec $\approx 0.67$ cm/sec. Therefore, a flow diameter of around 10 cm will translate to a production rate of 5 m$^3$/day, which in effect is an order of magnitude less than typical field production rates. Substantially larger magnets can be considered to resolve the issue, but this will noticeably increase the cost of the system. This approach is considered as a part of our broader development strategy. We also look at the possibility of sub sampling.

Alternatively, we suggest concentrating on the oil peak measurements instead and obtain water by difference. As the $T_1$ for heavy oil is typically in the range of $10 – 100$ ms, enough time is available to accommodate realistic flow rates in the wells. For example the same flow diameter can accommodate in excess of 113 m$^3$/day flow rates for a 100 ms relaxing oil. The proposed approach could be accommodated with the current design for fluid flow measurements.

The planned steps for testing this approach are as follows:

- Modify our available high temperature loop for the purpose of this testing (accurate flow rate measurement, temperature control).
- Analyse flow regimes in the tube and assess the effects of viscosity, flow composition, turbulence and residence time distribution on accuracy of measurements.
- Test the capabilities of our digital fluoroscopy system (possibly combine two of them for getting stereo-effect) of delivering flow rate measurements based on appropriate image correlation analysis.
- With the known flow rate and flow velocity distribution analyse possibility of water content extraction from NMR signal.
• Look into the problem of proper continuous sampling (if a bypass loop will be needed in order to reduce flow rate of fluid passing through the meter).

A successful design of such a meter will require a wider diameter pipe and a wider magnet but of similar length. The potential incremental cost will have to be investigated but it is not considered prohibitive.

7. CONCLUSIONS
NMR based fluid content and fluid measurement technology is now feasible. Properties such as fluid viscosity, solvent content and water-cut can be measured on-line with remarkable accuracy and precision. Additional field-testing will be required prior to full commercialization.

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NOMENCLATURE

- \( A_o \) Signal Amplitude of Oil
- \( A_w \) Signal Amplitude of Water
- \( AI \) Amplitude Index
- \( AI_w \) Amplitude Index of Water
- \( DC \) Direct Current
- \( m \) Mass \([g]\)
- \( \text{NMR} \) Nuclear Magnetic Resonance
- \( \text{PLC} \) Control System on Well Pad
- \( \text{RHI} \) Relative Hydrogen Index
- \( T_1 \) Spin-Lattice Relaxation Time \([\text{ms}]\)
- \( T_2 \) Transverse Relaxation Time \([\text{ms}]\)
- \( T_{2gm} \) Geometric Mean \( T_2 \) \([\text{ms}]\)
- \( \text{VAC} \) Volts Alternating Current
- \( w_c \) Water-cut

Greek Letters

- \( \alpha \), \( \beta \) Coefficients in Viscosity Models
- \( \mu \) Viscosity \([\text{mPas}]\)
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