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Fast measurements of average flow velocity by Low-Field ^{1}H NMR

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ABSTRACT

In this paper, we describe a method for measuring the average flow velocity of a sample by means of Nuclear Magnetic Resonance. This method is based on the Carr–Purcell–Meiboom–Gill (CPMG) sequence and does not require the application of any additional static or pulsed magnetic field gradients to the background magnetic field. The technique is based on analyzing the early-time behavior of the echo amplitudes of the CPMG sequence. Measurements of average flow velocity of water are presented. The experimental results show a linear relationship between the slope/*y*-intercept ratio of a linear fit of the first echoes in the CPMG sequence, and the average flow velocity of the flowing fluid. The proposed method can be implemented in low-cost Low-Field NMR spectrometers allowing a continuous monitoring of the average velocity of a fluid in almost real-time, even if the flow velocity changes rapidly.

1. Introduction

The influence of flow on the NMR signal has been a topic of study since several years ago. The first report of flow measurement by NMR was probably by Suryan [1] who measured NMR signals at about 20 MHz from water flowing in a U-tube between the pole pieces of a magnet. He observed that when partially saturated spins are replaced by unsaturated flowing spins, the continuous wave (CW) NMR signal increases. This principle was subsequently exploited by Singer [2] to demonstrate *in vivo* flow measurements. Hirschel and Libello studied the steady state NMR signal in the presence of flow as a function of fluid velocity [3,4]. The experimental results shown in these works indicate that flow velocity can be derived from calibration curves of signal intensity per unit volume if the spin–lattice relaxation time T_1 and the degree of saturation of the sample (λ) [5] are known along with the characteristic lengths of the main magnet and the rf coil. Arnold and Burkhart [6] described the effect of flow in the NMR signal using a spin-echo sequence and taking into account the spatial dependence of velocity under laminar conditions. This work was extended by Stejkal [7], Grover and Singer [8] and Packer et al. [9,10] using pulsed-field-gradient (PFG) techniques and a spin-echo sequence. The work of Hemminga et al. [11] is a direct extension of the work of Arnold and Burkhart [6]. They applied a difference method, which does not require magnetic field gradients, to measure flow rates in the presence of a stationary phase. The reported measured velocities with this method were up to 25 mm/s.

Since the first studies of flow by NMR, different methods to characterize and measure flowing fluids have been developed [12]. The majority of the NMR techniques for measuring flow rely on the application of static or pulsed magnetic field gradient superimposed to the main static magnetic field [13–15]. The essential idea, based on the work of Hahn [16] and Stejskal and Tanner [17], is to use static or pulsed magnetic field gradients to create a modulation of the spin magnetization, characterized by a magnetic wave vector k, which is proportional to encoding time and gradient strength. After a given evolution time the displacement of spin due to flow produces a phase shift of the modulation which can be measured from the NMR signal. The phase shift is proportional to the linear velocity and the wave vector k in the presence of symmetric displacement distributions. With the basic methods [12], the measurement of flow velocity requires a separate scan for each chosen modulation k and is, therefore, time consuming. Furthermore, these methods are only useful to measure flow under stationary conditions or flow velocities profiles which change slowly compared to the time required for data acquisition.

At present, NMR methods have long been employed to quantitatively measure flow rates, and several reviews of NMR as a tool for studying flowing fluids can be found in the literature [14,15,18–21]. Besides the works [12,14,15,18–21] and references therein, the works of Han et al. [22], Bagueira de Vasconcellos Azeredo et al. [23], Casanova et al. [24], Perlo et al. [25], Song and Scheven [26] and Galvosas and Callaghan [27] can be mentioned as examples of some more recent NMR techniques used to

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measuring flow, among many others. Bagueira de Vasconcellos Azeredo et al. [23] take advantage of the sensitivity to flow of the Continuous Wave Free Precession (CWFP) regime, in the presence of a magnetic field gradient. They show results under laminar regime conditions for flow velocities up to 10 cm/s. Han et al. [22] used NMR imaging techniques to study the rheology of blood under laminar and turbulent regimes and for stationary flow conditions, for velocities up to 300 cm/s. In that work, one method for flow characterization was to measure the velocity profile using a spin-echo based pulse sequence, containing flow-compensated slice selection in the main flow direction, flow compensated frequency encoding of the radial position, and phase encoding of the velocity in the main flow direction using bipolar gradients. Another method determines the statistical velocity distribution in the main flow direction using PFG techniques with flow-compensated slice selection. The reported time for obtaining one velocity profile or the statistical velocity distribution was 20 min. Casanova et al. [24] and Perlo et al. [25] implemented the so-called 13-interval PFG stimulated spin echo (STE) to obtain velocity profiles by ex situ NMR on flows under laminar regime condition and flow velocities up to 20 mm/s.

On the other hand, for many industry applications, the fast measurement of flow rates is required [13]. For such applications, Nuclear Magnetic Resonance (NMR) has proven to be a powerful tool. The main advantage of NMR with respect to other methods is that the flow pattern is not disturbed by the measurement process itself since there is no direct mechanical contact with the fluid. Regarding NMR techniques for rapid measurements of flow is important to mention the works of Song and Scheven [26] and Galvosas and Callaghan [27]. Song et al. [26] present a one-scan method for determining mean flow velocities within a few milliseconds in the presence of a static magnetic field gradient, and without the need of multiple scans. They make use of the Multiple Modulation Multiple Echoes technique (MMME) to produce a series of coherence pathways [28,29], each of which exhibits a phase shift that is proportional to fluid velocity. They show results under laminar flow regime conditions for mean flow velocities up to 0.06 cm/s. Even though the echoes belonging to different coherence pathways can be acquired in one scan, a scan for the stationary sample is used as a reference to calculate the phase shift of each echo in order to obtain the mean flow velocity value [26]. Galvosas and Callaghan [27] demonstrate the use of NMR velocity imaging techniques to measure flow at velocities on the order of 1 m/s. In this work, they use a technique called soft-pulse-quadrature-cycled PGSE-RARE (SPQC-PGSE-RARE). With the aid of this technique they show two-dimensional profiles of stationary flow under laminar regime conditions for mean flow velocities up to 65 mm/s. In the same work, they also make use of a modified PGSE technique involving two slice gradients to obtain the one-dimensional velocity profile of a free falling water jet for mean flow velocities up to 250 mm/s. These last results are also under laminar flow regime conditions and spatial fluctuations taking place on a time scale of the order of several seconds.

On the other hand, for the industry it is of particular interest to perform a real-time monitoring of a fluid passing through a pipe under high flow rate conditions. It is important to remark that in actual cases the diameter of the pipes can be of several centimeters. In this cases the requirements of homogeneity and linearity of the static magnetic field and magnetic field gradients, respectively might not be easily accomplished. Furthermore, a continuous monitoring of fluid flow imposes strong quality requirements on the NMR hardware. In large liquid volumes, under turbulent flow regime conditions, the coherence of the signal in the phase direction is severely disturbed by the strong and fast spatial fluctuations of the liquid. In such cases, phase difference appears no longer be an adequate velocity indicator. The present work constitutes an extension of previous works [6,11] pointing to measure flow velocity without the aid of magnetic field gradients. As we will explain later, the method substantially simplifies the requirements on the NMR spectrometer, making easy to implement it beyond laboratory conditions. The main goal of this work is to develop a fast method capable of measure the mean velocity of large volumes of fluids flowing both in laminar and turbulent regimes, under conditions of high flow rates and velocities rapidly changing. In order to accomplish our objective we focus ourselves on Low-Field NMR. Low-Field NMR (LF NMR), usually based on bench-top hardware, has become a versatile and fast solution for a large number of practical problems. The main advantage of LF NMR with respect to High-Field NMR (HF NMR) is its comparative low cost. On the other hand, the main drawback of LF NMR is the loss of sensitivity which limits its applicability in some cases. In practice, LF NMR is useful when samples are large and the nuclei have high natural abundance and high magnetogyric ratio as is the case for hydrogen nuclei (^1H).

In this paper, we study the effect of spin flow on the echo signal amplitudes resulting from the application of Carr–Purcell–Meiboom–Gill pulse sequences without using additional static or pulsed magnetic field gradients. We propose a simple method to measure the average flow velocity for plug and laminar flow regimes. The method determines flow velocities within seconds and can be easily implemented in a LF NMR spectrometer. It is intended for measuring flow rates in liquids containing hydrogen nuclei, such as water and oils, among other fluids.

2. Theory

2.1. Basic fluid dynamics

Under laminar conditions a Newtonian fluid moves smoothly in concentric layers or *laminae* through the cross section of a circular pipe. In this case, it can be shown that the shear stress is a linear function of the radial position r in the pipe, resulting in a parabolic velocity profile $v(r)$ [30]:

$$v(r) = \frac{\Delta p r_0^2}{4 l \eta}\left(1 - \frac{r^2}{r_0^2}\right) = 2 v_{avg}\left(1 - \frac{r^2}{r_0^2}\right) \quad (1)$$

Here, η is the dynamic viscosity, Δp is the pressure drop along the flow direction within a pipe length of l, r_0 is the radius of the pipe and v_{avg} denotes the average velocity over the cross section of the circular pipe. From this relationship the so-called Hagen–Poiseuille law results for the volume flow rate $\dot{V}$ [30]:

$$\dot{V} = \frac{\pi \Delta p r_0^4}{8 l \eta} \quad (2)$$

Laminar flow is present at low velocities. Turbulent flow, with much more complex behavior, occurs at higher flow rates, starting from a characteristic value called the critical Reynolds number Re_c. The transition from laminar to turbulent flow is governed by a combination of the fluid density ρ, dynamic viscosity η, the average flow velocity v_{avg}, and the pipe diameter d. The dimensionless relationship among these quantities is known as the Reynolds number (Re) [30], expressed as:

$$Re = \frac{\rho v_{avg} d}{\eta} \quad (3)$$

The Reynolds number can be understood as the ratio between the inertial force and viscous force and characterizes the friction effects in the fluid [30].

Turbulent flow is characterized by an unsteady and irregular eddying motion superimposed on the mean flow. A strongly flattened velocity profile, also called plug profile, is characteristic of turbulent flow. For Newtonian fluids in hydraulically smooth pipes the critical Reynolds number is $Re_c \approx 2300$, independent of the fluid.

2.2. Carr–Purcell–Meiboom–Gill sequence in the presence of flow

We will consider that the static magnetic field $\boldsymbol{B}_0$ is placed along the z-axis in the laboratory coordinates frame. It is well known that a Carr–Purcell–Meiboom–Gill (CPMG) sequence is composed by a $\pi/2$ radio-frequency (RF) pulse, a waiting period T_{cp}, and a subsequent train of π pulses separated in time by $2T_{cp}$ [31,32]. This sequence can be described as

$$\frac{\pi}{2}|_{x'} - T_{cp} - [\pi|_{y'} - 2T_{cp}]_N \tag{4}$$

where x', y' and z' are the rotating frame coordinates, and where the z' axis is chosen paralell to the z-axis. When a stationary liquid sample is subjected to a CPMG pulse sequence, and neglecting diffusion effects, the amplitude of the echo signal detected at the time $t = n2T_{cp}$ (where n is a natural number denoting the nth spin echo signal of the CPMG sequence) is given by

$$I(t) = \beta M_0 e^{-\frac{t}{T_2}} = I_0 e^{-\frac{t}{T_2}} \tag{5}$$

where β is a proportionality factor affecting the detection of NMR signals, M_0 is the equilibrium magnetization value attained in a static magnetic field $\boldsymbol{B_0}$, T_2 is the spin–spin relaxation time of the sample, and we set $I_0 = \beta M_0$.

When considering the effects of liquid flow in Eq. (5), we will distinguish two cases of interest, plug flow and laminar flow. The analysis relies on the following assumptions and simplifications:

1. The self-diffusion effects present in the fluid are ignored.
2. The spins of the flowing liquid have been subjected to an external magnetic field in such a way that a particular macroscopic value of the magnetization is attained before the spins enter the transmitter/receiver coil.
3. The rf field distribution $\boldsymbol{B_1}$ of the transmitter/receiver coil is roughly uniform inside the coil and vanishes outside of it.
4. Imperfections in rf pulses are disregarded.

2.2.1. Plug flow

For plug flow we consider that the liquid is moving with an uniform velocity $v = v_{avg}$. When a CPMG pulse sequence is applied to a flowing fluid (In this work we are concerned with nuclei of spin $I = 1/2$) the initial $\pi/2$ pulse will flip to the x–y plane the magnetization of the entire fluid that is present inside the probe coil. We will denote this instant as $t = 0$. The subsequent π pulses will not introduce new magnetization on the x–y plane because new flow elements entering the probe after the first $\pi/2$ pulse will be tilted by the π pulses along the -z direction.

In the following analysis we assume that the complete volume of the probe is filled with fluid, i.e., the fluid inside the probe does not contain void volumes. At the time $t = 0$, when the CPMG sequence is started, the total fluid volume will be $V(0)$. At a later time t, the volume of the remaining excited sample inside the probe will be:

$$V(t) = V(0) - Svt = V(0)\left(1 - \frac{v}{L}t\right) \tag{6}$$

In Eq. (6), S and L represent the cross section and the length of the probe coil, respectively, and v denotes the average velocity of the fluid. This reduction in excited fluid volume will modulate the CPMG signal decay. Taking into account expression (6), the signal of the CPMG sequence at time $t = 2n\ T_{cp}$ (n is a natural number denoting the nth spin echo signal of the CPMG sequence) will be given by:

$$I(v,t) = \beta M_0(v)V(t)e^{-\frac{t}{T_2}} = \beta M_0(v)V(0)\left(1 - \frac{v}{L}t\right)e^{-\frac{t}{T_2}} \tag{7}$$

In expression (7), $M_0(v)$ represents the magnetization per volume unit of the fluid flowing at the velocity v, and T_2 represents the spin–spin relaxation time of the fluid.

2.2.2. Corrections due to the polarization factor

Even though the probe coil is placed within a static magnetic field B_0, the moving fluid requires a polarizing stage in order to produce a detectable NMR signal in the probe coil. This can be achieved by positioning a polarizing magnetic field of length L_{pol} along the pipe carrying the fluid prior to the magnet containing the probe coil. Taking into account the average velocity v of the fluid, the fraction of magnetization along the z-axis, perpendicular to the flow velocity direction, will be given by the following equation:

$$f(v, L_{pol}, T_1) = \frac{M_0(v)}{M_0(0)} = \left(1 - e^{-\frac{L_{pol}}{vT_1}}\right) \tag{8}$$

In Eq. (8), T_1 denotes the spin–lattice relaxation time of the flowing fluid. The $f(v,L_{pol},T_1)$ factor will be referred to as the *pre-polarization factor* and will be denoted as $f(v)$. Including $f(v)$, the spin echo amplitudes of the CPMG sequence at the time t will be given by:

$$I(v,t) = \beta f(v)M_0(0)V(0)e^{-\frac{t}{T_2}}\left(1 - \frac{v}{L}t\right) \tag{9}$$

In expression (9), $M_0(0)$ denotes the equilibrium magnetization of the fluid at rest, placed in the static magnetic field of the pre-polarizing stage. In addition, for a given average fluid velocity v, expression (9) shows that a linear modulation of CPMG signal envelope is to be expected whenever that the condition $t \ll T_2$ is fulfilled.

Fig. 1 shows plots of the pre-polarization factor $f(v)$ as a function of flow velocity for some values of the longitudinal relaxation time T_1 and for two values of the pre-polarization length ($L_{pol} = 0.5$ m and $L_{pol} = 0.75$ m). It can be seen that for the same values of longitudinal relaxation time and velocity, the initial magnetization increases with the pre-polarization length L_{pol}. From an experimental point of view, the length L_{pol} of the pre-polarization stage needs to be chosen as a compromise between experimental resources and the desired signal-to-noise ratio (SNR) according to the velocity range of the fluid to be measured.

2.2.3. Laminar flow

For the calculation of the NMR signal for laminar flow we adopt an iterative approach explained in Appendix A. In this cases, the velocity profile is given by Eq. (1). Under these circumstances, and disregarding imperfections of the rf pulses in CPMG sequence, the magnetization initially excited by the $\pi/2$ pulse of a CPMG sequence at $t = 0$, and the magnetization that remains inside the probe coil at time $t(n) = n\Delta t$ can be calculated from Eq. (12) in Appendix A.

3. Experimental

In order to perform the experimental measurements, a flow loop including a centrifugal pump capable of providing stable flow rates of approximately 0.7–1.5×10^{-3} m^3/s was set up. The inner diameter of the pipe was 0.034 m. A solenoidal transmitter/receiver probe coil of $L = 0.08$ m was wound around the pipe. The NMR experiments were carried out in a horizontal bore 0.225 T permanent magnet (homogeneity of 750 ppm) with a home-made NMR console with a quadrature receiver. The direction of the main magnetic field of 0.225 T was orthogonal to flow direction. In order to adjust the SNR of the NMR signal to satisfactory values within the available range of fluid velocities provided by the centrifugal pump (0.8–1.65 m/s), the pre-polarization factor was adjusted by placing a polarizing stage of L_{pol} = 0.5 m prior to the 0.225 T main magnet. The polarizing stage was made with a set of permanent magnets providing a magnetic field $B_{pol} \approx 0.33$ T pointing parallel to the main magnetic field and with a homogeneity of 3000 ppm.

As explained in Section 2.2.2, the splitting of polarizing stage and detection coil allows choosing a proper pre-polarization length according to the range of fluid velocities intended to be measured with an acceptable signal-to-noise ratio. Due to experimental limitations, in this work the pre-polarization length was set L_{pol} = 0.5 m. Whereas the homogeneity of the main magnetic field needs to be below the available irradiation bandwidth of the rf pulses, the homogeneity requirements are less restrictive for the pre-polarization magnet. The CPMG sequences was composed by pulses of $\pi/2$ and π of 25 and 50 μs, respectively, with a time interval T_{cp} of 200 μs (i.e., an inter-echo spacing of 400 μs). The phases of the $\pi/2$ and π pulses were chosen as 0° and 90° in the rotating frame, respectively. In order to correct base line and gain difference between the two receiver channels in quadrature, each measurement was performed from four CPMG trains following a CYCLOPS phase cycling scheme [12] with a repetition time of 0.5 s.

The mean relaxation times for the sample of water used in these experiments were T_1 = 1.44 s and T_2 = 0.65 s and bulk flow rates were determined by measuring the rate of filling of calibrated cylinders. On the other hand, under the experimental conditions of the present work the Reynolds number was in the range $2700 \leqslant Re \leqslant 5600$ so experimental measurements were performed under turbulent regime conditions.

4. Results and discussion

In order to study the effect of flow in the NMR signal, simulations of NMR signals resulting from a CPMG sequence in the presence of flow were performed at several average velocities in the range 0.5–2 m/s for geological formation water (T_1 = 1.44 s and T_2 = 0.65 s). In these simulations we assume a unit value of the initial magnetization for all average velocities, which means that we have assumed a pre-polarization factor $f(v) = 1$ for all velocities simulated. We have used N = 10000 and N_r = 1000 for simulations in the laminar regime (see Appendix). Any variation of these numbers did not show appreciable changes in the simulated signals.

Figs. 2 and 3 show plots of the simulated NMR signals for four typical average flow velocities of 0.5, 1, 1.5 and 2 m/s. Fig. 2 shows the results corresponding to plug flow, whereas Fig. 3 shows the results for laminar flow. The insets in Figs. 2 and 3 show the simulated NMR signals in the range 0–0.015 s (where clearly the condition $t \ll T_2$ is fulfilled). This data shows that the first part of the simulated NMR signals exhibits a linear dependence of signal amplitude with time both for plug and laminar flow (Figs. 2 and 3).

For several average velocities (0.5–2 m/s) we fitted the linear region of the simulated signal envelope in the range 0–0.015 s for both plug flow and laminar flow regimes. The fitting expression was of the form $I(t) = A + Bt$. From Eq. (9) and within the linear approximation $A = \beta f(v)M_0(0)V(0) = I(v,0)$ and $B = -I(v,0)v/L_{eff}$ so the ratio $-B/A = v/L_{eff}$ (i.e. the ratio -B/A turns out to be proportional to the average flow velocity), being L_{eff} the effective length of the transmitter/receiver rf coil which, in practice, will depend on the magnetic properties of the fluid to be measured and on the geometry of the rf coil. Fig. 4 shows a plot of the quotient $-B/A$ obtained from simulated echo amplitudes as a function of the average flow velocity of the fluid for both regimes. It can be seen that there is a linear relationship between the quantity $-B/A$ and the average velocity of the fluid both for plug and laminar flow regimes.

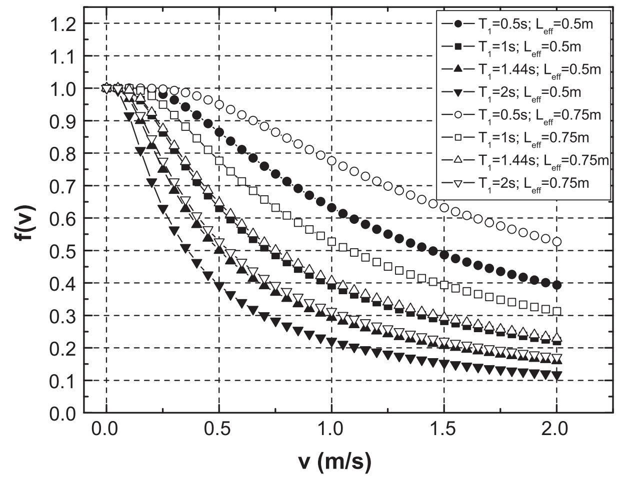

Fig. 1. Plots of the pre-polarization factor $f(v)$ as a function of flow velocity for some values of the longitudinal relaxation time T_1 and for two values of the pre-polarization length (L_{pol} = 0.5 m and L_{pol} = 0.75 m). Full circles: T_1 = 0.5 s; L_{eff} = 0.5 m. Full squares: T_1 = 1 s; L_{eff} = 0.5 m. Full up triangles: T_1 = 1.44 s; L_{eff} = 0.5 m. Full down triangles: T_1 = 2 s; L_{eff} = 0.5 m. Hollow circles: T_1 = 0.5 s; L_{eff} = 0.75 m. Hollow squares: T_1 = 1 s; L_{eff} = 0.75 m. Hollow up triangles: T_1 = 1.44 s; L_{eff} = 0.75 m. Hollow down triangles: T_1 = 2 s; L_{eff} = 0.75 m.

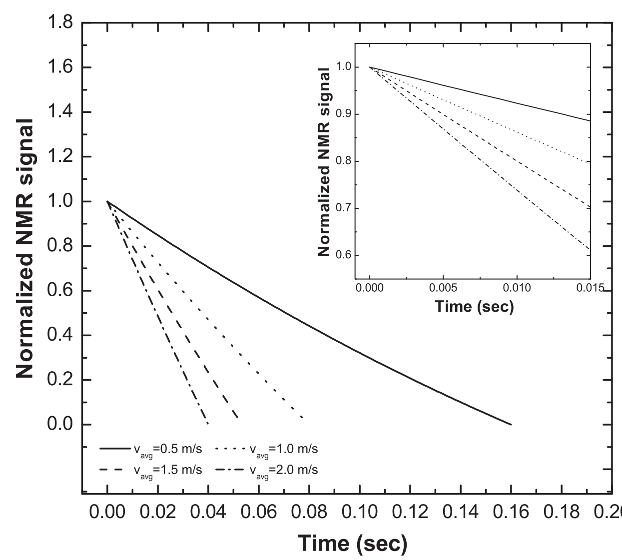

Fig. 2. Plots of the simulated echo amplitudes following a CPMG pulse sequence for four typical average flow velocities of 0.5, 1, 1.5 and 2 m/s in the plug flow regime. The inset shows the simulated signals in the range 0–0.015 s.

The NMR measurements for geological formation water were performed for average velocities in the range 0.8–1.65 m/s. Fig. 5 shows a typical plot of the echo signals following a CPMG sequence for water flowing at an average velocity of 1.2 m/s. The inset plot in the Fig. 5 shows the echo signals at the first 15 ms of data acquisition. The dashed line is a guide to the eyes, and illustrates the linear behavior of the NMR signal envelope at the beginning of the CPMG sequence. This feature was found for all flow velocities studied.

A linear fit of form $I(t) = A + Bt$ of the echo amplitudes of the linear region of the CPMG signal envelope was performed. Sensitivities to including or excluding odd-numbered echoes [33] were tested and were found insignificant, and fitting the first seven even-numbered echo amplitudes was established as a routine. Fig. 6 shows a plot of the quotient $-B/A = v/L_{eff}$ obtained from fitting the initial CPMG signal decay of formation water as function of average flow velocity. The experimental data shown in Fig. 6

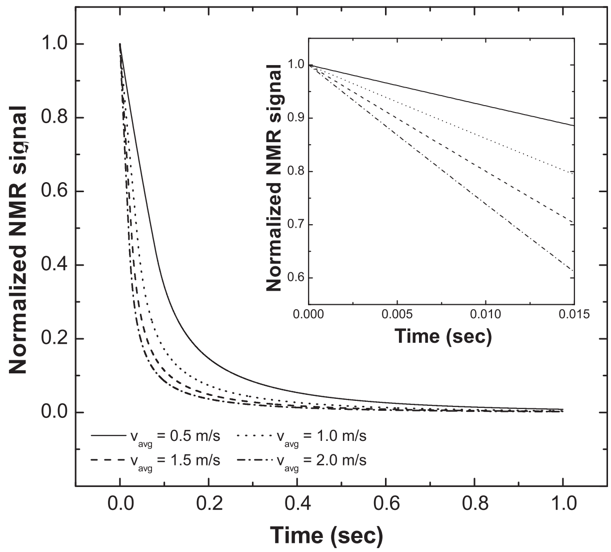

Fig. 3. Plots of the simulated echo amplitudes following a CPMG pulse sequence for four typical average flow velocities of 0.5, 1, 1.5 and 2 m/s in the laminar flow regime. The inset shows the simulated signals in the range 0–0.015 s.

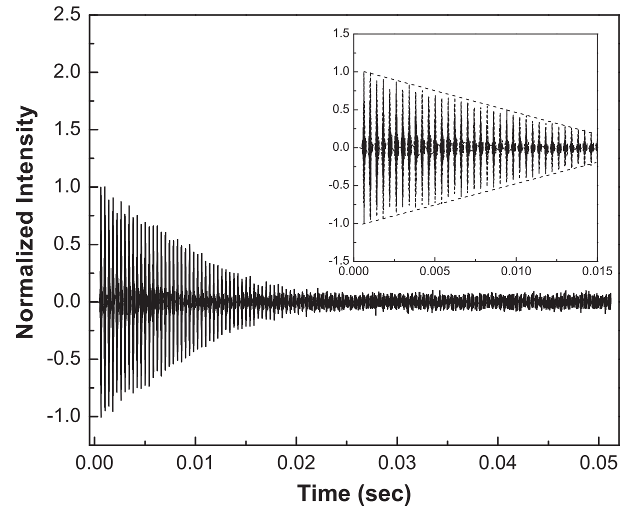

Fig. 5. Typical plot of the echo signals following a CPMG sequence for a sample of water of geological formation flowing at an average velocity of 1.2 m/s.

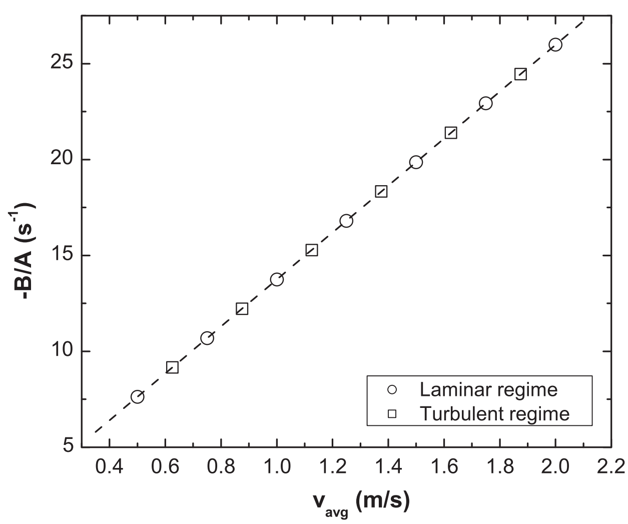

Fig. 4. Plot of the quotient $-B/A$ obtained from simulated echo amplitudes as a function of the average flow velocity of the fluid. The circles show the results for laminar flow whereas the squares show the results for plug flow. Dashed line represents the linear fit of data points.

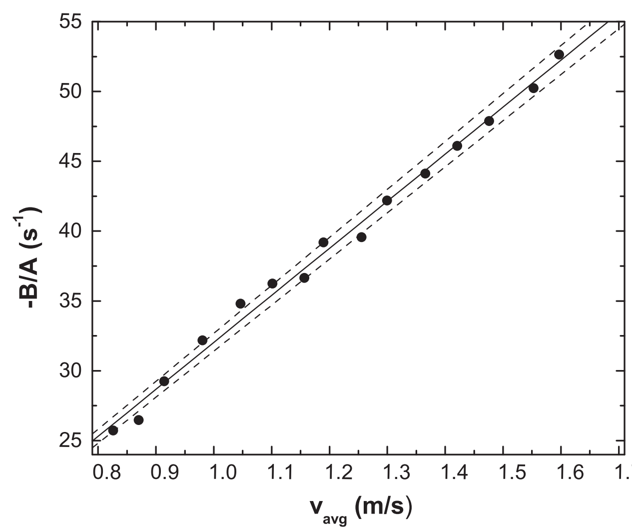

Fig. 6. Plot of the quotient $-B/A$ obtained from experimental data for the water of geological formation as a function of the average flow velocity experimentally determined by measuring volume flow rate. Solid line represents the linear fit of data points. Dashed lines indicate the range ±2% from linear fit.

confirms the modeling results presented in Fig. 4. Experimental results show that if the effective length of the transmitter/receiver probe coil L_{eff} is known, the average flow velocity of the fluid can be easily obtained from equation:

$$v_{avg} = \left(-\frac{B}{A}\right)L_{eff} \tag{10}$$

However, as we mentioned before, the L_{eff} depends on the geometry of the transmitter/receiver rf coil and on the magnetic properties of the fluid to be measured. One way to overcome the need to determine the value of L_{eff} consists of performing a linear fit of the values of $-B/A$ obtained from the experimental data as a function of the actual average flow velocities. This linear fit is shown as a solid line in Fig. 6. The fitted expression was in the form $-B/A = C + D\ v_{avg}$. In the last expression C takes account of any small velocity offset and $D = 1/L_{eff}$. The eighty percent of the experimental results lie within ±2% marked by the dashed lines in Fig. 6. As a consequence of the results, once the parameters C and D are calculated, it is straightforward to experimentally obtain the average flow velocity from analyzing the initial CPMG signal decay acquired on the flowing fluids as:

$$v_{avg} = \frac{-B/A - C}{D} \tag{11}$$

5. Concluding remarks

In this work we have proposed a fast method to measure, in almost real-time, the average flow velocity under turbulent regime conditions even if flow velocity changes rapidly with time. Even though experimental results were obtained under turbulent regime conditions, as spatial fluctuation under laminar regime conditions are expected to be smaller than under turbulent conditions, the theoretical framework suggest that the method can be easily extended to determine average flow velocities under laminar regime conditions. Addressing this last point, experimental determination of average flow velocities under laminar regime condition were obtained with the same method with a different experimental set up. This results will be published in a future work.

We have demonstrated the ability to derive flow velocities by analyzing the initial CPMG decay acquired on the flowing liquids. This approach does not require the application of any static or pulsed magnetic field gradients. We have used two simple models for plug and laminar flow regimes to describe the behavior of the echo amplitudes of a CPMG sequence in the presence of flow. The results show that a linear behavior of the initial echo amplitudes of the CPMG sequence should be expected both for plug and laminar flow. Furthermore, the ratio between the slope and the *y*-intercept of the linear fit of the initial CPMG decay is proportional to the average velocity of the fluid.

Based on these findings, we have implemented a method for measuring the average velocity of fluids without the need for any static or pulsed magnetic field gradients. We have compared simulation results with experimental measurements on geological formation water flowing at velocities between 0.8 and 1.65 m/s. The experimental results confirm the linear behavior of the initial CPMG decay that was theoretically predicted. The average velocity of the flowing fluid is proportional to the quotient of slope and y-intercept of the fit of the linear region of the CPMG signal decay. The results show that after calibration, it is possible to monitor the average flow velocity with an error within ± 2% and a time resolution in the order of seconds.

On the other hand, the splitting of pre-polarization stage and detection coil allows determining the range of fluid velocities intended to be measured with a satisfactory SNR by properly chosing the length L_{pol} of the pre-polarization stage. In addition, as long as the SNR is acceptable a precise knowledge of the longitudinal relaxation time T_1 of the fluid is not needed. Due to the proposed method does not need the use of static or pulsed gradients, the requirements on the hardware of the NMR spectrometer are rather little restrictive. Whereas the homogeneity of the main magnetic field needs to be below the available irradiation bandwidth of the rf pulses, experimental results show that, in fact, the homogeneity requirements for the pre-polarization magnet are not very restrictive. As a consequence, the proposed method can be implemented in low-cost LF NMR spectrometers and can be used to continuously monitoring the average velocity of a fluid. As a final comment, the possibility of performing a continuous monitoring of average flow velocity is of particular interest in oil industry.

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Appendix A

A.1. Calculation of NMR signals in the presence of flow for laminar regime

In order to simulate the CPMG signal decay for laminar liquid flow in a circular pipe we follow a discrete approach to the problem. We consider that the static magnetic field B_0 is along *z*-axis and is perpendicular to the transmitter/receiver probe coil axis placed parallel to flow direction along *y*-axis in the laboratory frame. Disregarding errors of the initial rf pulse of $\pi/2$ at the beginning of the CPMG sequence, we consider that after this pulse ($t = 0$) all the magnetization inside the probe coil will be rotated into the transverse *x*–*y* plane in the laboratory frame.

In order to calculate the time evolution of the NMR signal, we have divided the cross section of the pipe of radius r_0 in a large number N_r of thin circular rings. The fluid within each ring of radius r_i across the circular pipe section will flow at a velocity $v(r_i)$ given by Eq. (1). The time evolution of the NMR signal in the rotating frame in the time interval $0 \leqslant t \leqslant T_f$ was obtained by calculating the remaining excited volume inside the probe coil after very short time intervals of size $\Delta t = T_f/N$, where N is a natural number. At time $t(n) = n\Delta t$ the excited volume inside the probe coil will be obtained by subtracting the excited fluid leaving the probe coil during the time Δt to the previous excited volume at time $t(n-1)$. If we disregard imperfections of the π pulses in CPMG sequence, the fresh liquid entering the probe coil will produce no detectable magnetization in the *x*–*y* plane. With these assumptions, the magnitude of detected NMR signal at time $t = n\Delta t$ will be given by the following algorithm:

$$M(n) = M_0 V(n) e^{\frac{n\Delta t}{T_2}} \tag{12}$$

where $V(0) = V_0 = \pi r_0^2 L$, which means the total volume initially excited by the $\pi/2$ pulse in the CPMG sequence, $V(n) = V(n-1) - f(n)$ and $f(n)$ is given by:

$$f(n) = 2\pi v_{avg} \sum_i \left(1 - \frac{r^2}{r_0^2}\right)(r_i^2 - r_{i-1}^2)\Delta t(1 - \Theta(n\Delta t - t_{f_i})) \tag{13}$$

where Θ is the Heaviside function, L is the length of the probe coil, $t_{f_i} = L/v(r_i)$ and $v(r_i)$ is given by Eq. (1).

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