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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]:

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

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]:

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

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:

$$Re = \frac{\rho\, v_{avg} d}{\eta} \tag{3}$$

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