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Fast magnetic resonance imaging and velocimetry for liquids under high flow rates

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Abstract

We here demonstrate the use of NMR velocity imaging techniques to measure flow in a free falling jet of water at speeds up to and on the order of 1 m/s. In particular, we show how to adapt the RARE imaging method, based on a CPMG multiple rf pulse train, so that the real and imaginary parts of the signal may be suitably acquired, enabling pulsed gradient spin echo encoding for flow. We term this method "soft-pulse-quadrature-cycled PGSE-RARE" or SPQC-PGSE-RARE. We further demonstrate the use of a one-dimensional (slice selective) imaging method which takes advantage of the cylindrical symmetry of the flow, and considerably shortens the image acquisition time.

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1. Introduction

NMR velocimetry has proven of considerable use as a tool for fluid mechanics investigations. Both the Lagrangian and Eulerian perspectives are available, using pure pulsed gradient spin echo encoding in the former case, and velocity imaging in the second. Ideally, velocity imaging allows one to determine the spatially dependent flow field $\boldsymbol{u}(\boldsymbol{r}, t)$ of the fluid under study where $\boldsymbol{u}(\boldsymbol{r}, t)$ is the velocity at each individual point in space (in the Eulerian picture). This simplifies to $\boldsymbol{u}(\boldsymbol{r})$ in case of a stationary flow where the velocity is time independent. Of course in practice, the resolution of velocity imaging may be limited, either by signal-to-noise or gradient strength availability in the case of spatial coordinates, or by the finite time needed for position encoding in the case of temporal information. It is the latter limitation which concerns us in this paper, where we address the subject of NMR velocimetry in rapidly flowing liquids.

The goal of our investigation is to study a free liquid jet. The knowledge of its flow field and the changes to that flow introduced by added surfactants permits a study of a phenomenon known as the "Marangoni effect" [1]. The technique demonstrated here is aimed at a study of this effect via the changes of the properties of the liquid jet and, in particular, its dependency on the type of surfactant and its concentration. The results of these experiments in regard to the fluid dynamical properties will be published elsewhere. In contrast, the focus of this present article concerns the different NMR pulse sequences that are shown to accomplish the monitoring of liquids in an approximately stationary flow field under flow rates of ≈500 mm/s where "flow rate" describes here the spatially dependent time invariant velocity $\boldsymbol{u}(\boldsymbol{r})$ within the flow field. Subsequently, the mean or averaged flow rate describes the averaged velocity $\bar{\boldsymbol{u}} = \int_A \boldsymbol{u}(\boldsymbol{r})\mathrm{d}\boldsymbol{r} / \int_A \mathrm{d}\boldsymbol{r}$ of the liquid flowing through a certain plane A. The challenge for these measurements is twofold. First, the high velocity results in a limited time during which

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the spins stay in the rf-coil. Second, we have to deal with fluctuations of the free jet. This means that even in the case where we attempt to establish a stationary flow field (laminar flow), the whole jet jitters slightly thus placing some constraints on the pulse sequences used. Measurements in a rigid geometry such as pipes are therefore much easier to handle even in cases of high velocities.

Velocity profiles have been measured using NMR on various samples and over a wide range in velocity [2–9]. The very first experiment was performed by Hayward and Packer [10] who used pulsed gradient spin echo (PGSE) NMR encoding to deduce the distribution of velocities, without directly obtaining an image. Early NMR microscopy experiments on pipe flow were performed by Callaghan et al. [11]. In this article we shall be concerned with rapid velocimetry, and amongst the fastest known imaging techniques is RARE [12]. Scheenen et al., used the rapid imaging method RARE [12] combined with both pulsed gradient stimulated echo (PGSTE) encoding [13] and a modified PGSE encoding [14] for the investigation of flow processes. However, they studied the water uptake in plant stems e.g., liquids under very small flow rates (on the order of ≈0.5 mm/s). Sederman et al. [15] investigated pipe flow with a SEMI-RARE sequence, without PGSE encoding. In their work the flow profile is directly obtained by acquiring successive NMR images and by employing the image contrast introduced by different fluids having different T_2. These authors measured velocities ≈40 mm/s. Han et al. [16] studied the rheology of blood in pipes of various diameters. They obtained projections of velocities in 1D profiles as well as 1D velocity distributions with maximum velocities of up to 3.5 m/s. Xia and Callaghan [17] used a similar setup and geometry to the setup in this work. They determined the velocity field in a visco-elastic liquid building up a tubeless siphon.

We describe two approaches to imaging rapid flow in this paper. Both are based on a PGSE pulse sequence used to phase encode for the velocity. This phase is introduced into the NMR signal in proportion to the applied magnetic field gradient amplitude g and is given by the expression

$$\exp\{-i2\pi \boldsymbol{q}\cdot\boldsymbol{u}\Delta\} \quad \text{with} \quad \boldsymbol{q}=\tfrac{1}{2\pi}\gamma\delta\boldsymbol{g}, \tag{1}$$

where δ is the duration of the gradient pulse, Δ is the observation time, γ is the gyromagnetic factor and $\boldsymbol{q}$ is the scattering wave vector (see Fig. 3 for details of the timing). Subsequent Fourier transformation of the acquired NMR signal with respect to $\boldsymbol{q}$ delivers the propagator $\bar{P}(\Delta\boldsymbol{r},\Delta)$, depending on the displacement $\Delta\boldsymbol{r}$. In particular, due to the experimental setup with $\boldsymbol{q}=(0,0,q_z)$, we obtain $\bar{P}(\Delta z,\Delta)$ depending on Δz as the displacement in z-direction and hence, when we combine this encoding with some imaging modality, we are able to obtain u_z at each point of the image (see [18]).

The first pulse sequence to be described employs the RARE sequence in which a prior PGSE segment is used for the velocity encoding. Conventional wisdom has it that such encoding is difficult since the (multi-echo) RARE sequence delivers the real part of the NMR signal unscathed while the imaginary part suffers artifactual attenuation due to rf pulse errors. We shall show later how we address this problem. In the meantime, we note that the RARE approach allows us to measure two-dimensional velocity profiles and was used in experiments with velocities of up to ≈50 mm/s. Although this pulse sequence is very useful for velocities in this range, the velocities occurring in a free liquid jet are much higher. Therefore a second, much simpler, pulse sequence is described here that is used to measure the velocity in only a small strip of the sample, thus providing a one-dimensional velocity profile. Of course, for a liquid jet of circular cross section, this limitation to 1D is not a disadvantage, since the rotational symmetry of the jet should not require a full two-dimensional velocity map. A similar approach was used by Dusschoten et al. [19] for the measurement of displacements in soil model systems.

2. Experimental

All experiments were carried out on a Bruker AMX NMR system at a ^{1}H frequency of 300.14 MHz. The magnet was equipped with a Bruker three axis micro imaging system "Micro 2.5" that provides gradients of up to 1 T/m. The rf resonator used for all experiments has a inner diameter of 15 mm and a height of 20 mm. A glass tube with an outer diameter of 15 mm and an inner diameter of 13.5 mm was fitted right through the resonator providing a "wettable" environment within the magnet.

Two experimental setups were used, one for investigation of the free jet and the other, a less demanding pipe flow for testing of the pulse sequences. For investigation of the free jet, a capillary with inner radius $R = 2$ mm was placed in the magnet in such a way that the lower end of the capillary, and hence the upper end of the free liquid jet, is adjusted to the upper end of the rf resonator (see Fig. 7 for a longitudinal section of the jet). A constant laminar flow in the feed pipe was maintained through the use of a gear pump (Cole–Parmer digital dispensing drive with pump head from Micropump, type 184). The jet was captured in a fluid reservoir 50 mm below the end of the capillary i.e., the jet was free for a length of 50 mm without break up. Suppressing the break up by catching the jet in a liquid reservor minimizes spatial fluctuations. A remaining fluctuation, referred to above as "jitter," was observed and just visible with the naked eye. It is a sudden horizontal movement of the jet which occasionally happens on a time scale of several seconds. This setup resulted in an averaged flow rate of $\bar{u} \geqslant 100$ mm/s. Because of

$$u(r)=u_{\max}[1-(r/R)^2] \quad 0\leqslant r\leqslant R \tag{2}$$

for a parabolic laminar flow in a capillary, where $u_{\max}=2\bar{u}$ is the maximum velocity and r the radius, velocities of at least 200 mm/s need to be measured. This consideration