DOI 10.5162/sensoren2024/P03

Magnetic Flow Metering with Optically Pumped Magnetometers

Leonhard Schmieder[1], Peter A. Koss[1]
[1]Fraunhofer IPM, Georges-Köhler-Allee 301, 79110 Freiburg im Breisgau, Deutschland
Leonhard.Schmieder@IPM.Fraunhofer.de

Abstract

This article covers the recent advances of the research on magnetic flow metering. The procedure was analyzed to determine the influence of setup conditions on RF pulsing flowing media. It shows that the flow profile plays a predominat role on the pulsing efficiency which lays the foundation on further research on a flow profile sensitivity of the metering method described.

Keywords: Flow Metering, Quantum Sensing, Magnetometry, Low-Field-NMR, Flow Profile

Introduction

This article covers a recapitulation of the studies conducted in [1,2]. The studies introduce a new magnetic field-based flow metering method using optically pumped magnetometers (OPMs) to detect signals. The method involves creating nuclear polarization in the fluid by exposing it to a strong magnetic field, then applying radiofrequency (RF) pulses to generate local magnetic marks used as timestamps for measuring flow velocity with a time-of-flight (TOF) method. This novel approach contrasts with traditional nuclear magnetic resonance (NMR)-based metering, where flow velocities are derived from spin precession phases detected using RF coils based on the Faraday induction principle. NMR-based metering, developed in the 1960s [3] for industrial use, has evolved to include commercial systems capable of measuring various phases such as gas, liquids, and oil [4]. Next to a recap of the flow metering method described the article shows simulation models to map flip angle distribution in the medium, similar to field mapping in clinical MRI systems, to evaluate the effects of RF pulses on magnetization distribution. This new mapping

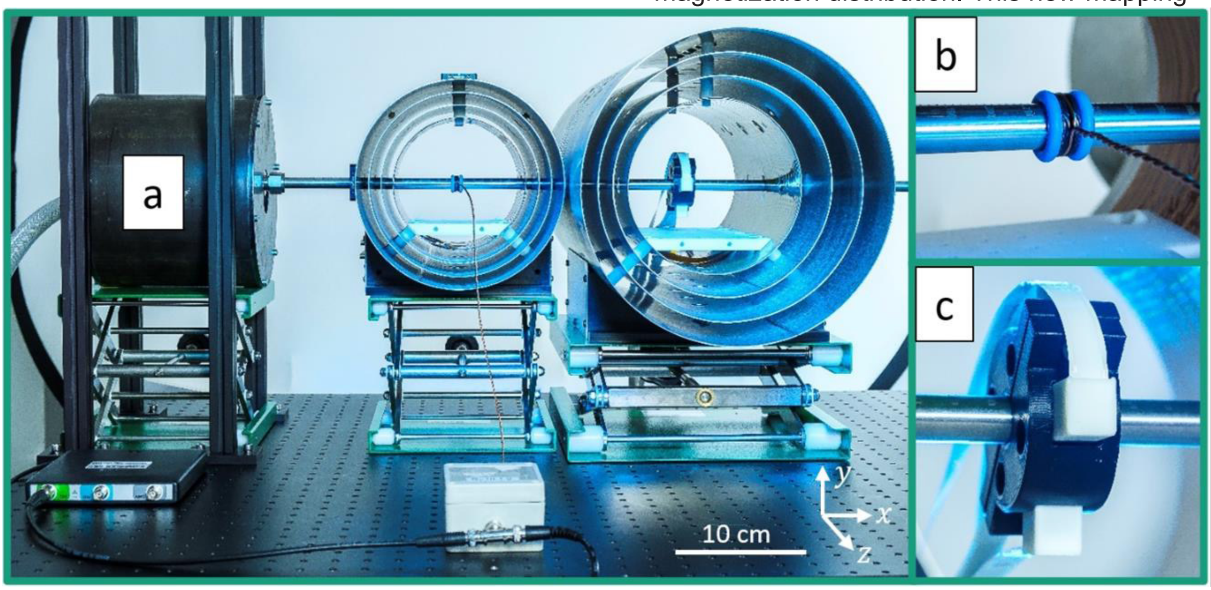

Fig. 1: The laboratory setup of a magnetic flow metering apparatus. In (a), a strong magnet ii housing is pre-polarizing the water, which traverses the setup from left to right in a 1/2 in. steel pipe. In (b), a close-up of the RF coil with a single turn is visible. The RF coil is operated in the left magnetic shield. In (c), the OPM mount around the pipe is displayed. Image and caption taken from [1] fig. 1.

DOI 10.5162/sensoren2024/P03

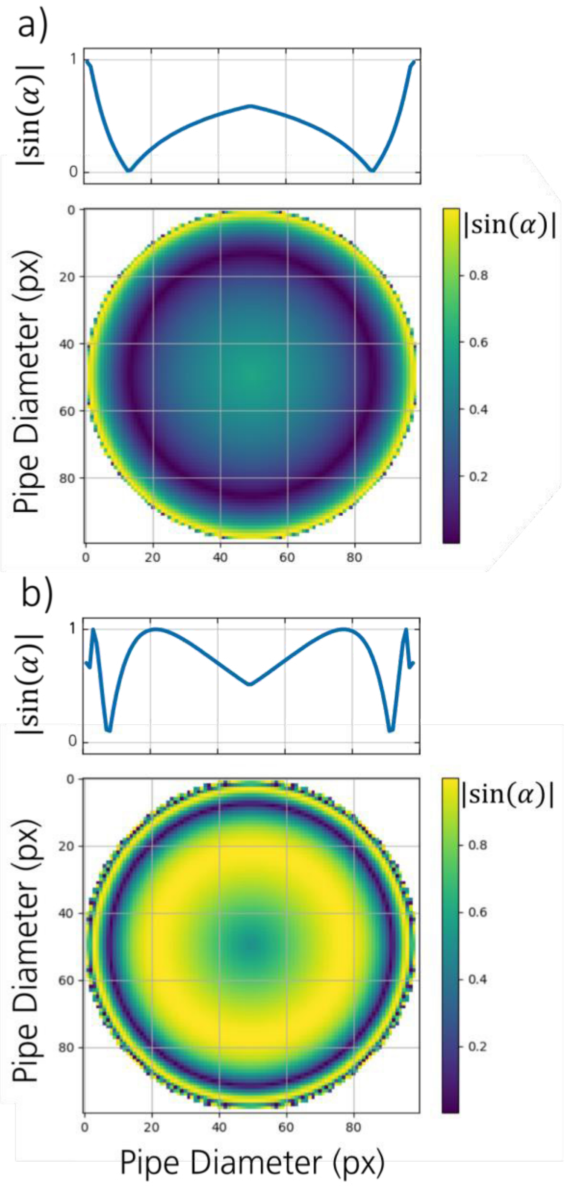

Fig. 2: *Flip angle projection distribution. In (a), the projection of a flip angle map with a cross-sectional plot of an effective 180° pulse is shown. The influence of different retention times in the B_1 field leads to an inhomogeneous radial distribution of the water magnetization orientation. In (b), the magnetic signal contribution map of an effective 450° pulse is displayed. Image and caption taken from [1] fig. 5.*

method, based on an analytical model of resonant RF excitation, assesses the influence of flow velocity and profile on the magnetic signal, comparing simulation results with experimental data to establish flow profile sensitivity. This approach marks the first of its kind in the field.

Methods

The simulation model features a magnetic flow metering setup, which can be seen in Fig. 1. There, water is pumped through a 9.4 mm stainless-steel pipe and pre-polarized using a 1 T permanent magnet. A resonant RF-pulse alters the water's magnetic properties, which are detected by an OPM downstream. The OPM, enclosed in two magnetic shields, measures changes in magnetic field strength affecting laser transmission through polarized alkali atoms. The system utilizes a solenoid to generate RF pulses within a controlled magnetic environment, achieving a resonance frequency around 5.6 kHz.

The simulation involves manipulating the magnetic properties of a fluid in a pipe and detecting changes using an OPM. The setup includes RF pulsing to generate a magnetic signal and an OPM downstream for detection. The pipe's cross-section is divided into a point grid, where for each grid point, the magnetization rotation angle is calculated based on the RF field, flow profile, and magnetization trajectory. In the detection phase, the OPM sensor output is determined from the magnetization distribution and sensor sensitivity. The flip angle α is calculated using the gyromagnetic ratio γ, RF pulse's magnetic amplitude $B_1(x,r)$, and retention time.

$$\alpha(r) = \int d\alpha(r) = \gamma / v(r) \int B(x,r) dx$$

The RF field is assumed constant during medium transit, and radial field components are negligible due to the coil's design relative to the pipe size. The turbulent medium's flow profile is fully developed.

Results

In Fig. 2 two simulated flip angle projection distributions are displayed for an effective 180° and 450° pulse. Due to the radially decreasing flow velocities in the pipe, the interaction times of the RF pulse vary accordingly. This effect creates an inhomogeneous radial flip angle pattern in the excited segment, which becomes more pronounced at higher effective flip angles. The magnetization of the medium does not rotate homogeneously. Comparing the influence of the RF pulse parameters to the resulting magnetic state in the medium shows that the flow profile plays a predominant role.

For evaluation experimental sweeps were conducted over the RF pulse amplitudes with flow velocities between 0.5 to 1.35 m/s, applying a voltage range of 1 to 600 mV in 25 mV increments to the RF coil. Each voltage step activated the coil for 10 seconds to measure the OPM signal amplitude, calculated

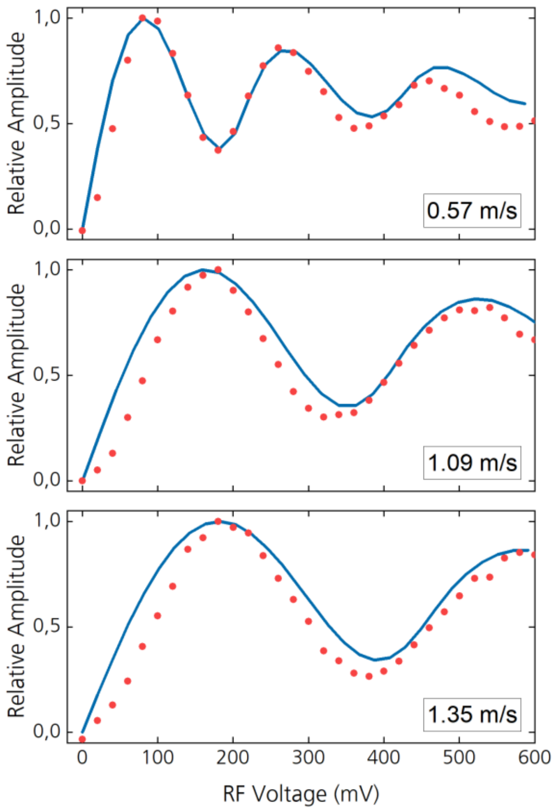

Fig. 3: Comparison of the experimental B_1 sweeps (red) with the simulation results (blue). The simulation is processing the oscillating medium magnetization in terms of frequency, proportion, and reduction of the medium signal amplitude consistently. Maximum amplitudes of the magnetic signals range from 120 pT at 0.57 m/s to 45 pT at 1.35 m/s and are normalized to 1. Image and caption taken from [1] fig. 7.

as the difference between signals with and without RF coil activation (see Fig. 6). Results, displayed in Fig. 7, were scaled to match the simulation's first maximum with experimental data at 0.57 m/s, using the same scaling for other velocities. Results indicate consistent magnetization oscillations across velocities, with effective pulses ranging from 150 mV at 0.57 m/s to 190 mV at 1.35 m/s. The model effectively replicates experimental conditions and validates the connection between magnetization and flow profiles. However, experimental results show a more concave magnetization curve compared to simulations, suggesting potential improvements in the model and its assumptions, particularly concerning field strength dependencies before effective pulses.

Discussion

The study demonstrates that the analytical mapping simulation model effectively captures the physical processes during RF pulsing in a flowing medium. It accurately models the frequency, amplitude reduction, and the ratio of maximum to minimum magnetization values. Specifically, it quantitatively illustrates how the flow profile impacts RF pulsed magnetization, setting a foundation for future research on flow profile sensitivity in magnetic signals.

RF pulsing in flowing media results in a magnetization pattern distinct from static conditions, with flow velocity variations causing a wide distribution of flip angles in a radial pattern and multiple revolutions within each segment. These insights from the simulation are critical for optimizing experimental setups and influencing factors in signal preparation and detection.

Future work will aim to enhance the simulation model and expand methodologies for quantum magnetometry experiments, incorporating conventional NMR techniques. This study marks the first successful use of a mapping approach in zero-to-ultra-low-field magnetometry with NMR, to the best of our knowledge.

Funding

This work was supported as a Fraunhofer LIGHTHOUSE PROJECT (QMag). In equal parts, this work was funded by the Ministry of Economic Affairs, Labour and Housing of the State of Baden-Württemberg, Germany.

References

[1] Schmieder L. et al., Radio frequency pulse marking of nuclear magnetization for magnetic flow metering: The impact of the flow profile. J. Appl. Phys. (2024); 135 (16): 163902. https://doi.org/10.1063/5.0204641

[2] Schmieder L. et al., Noninvasive Magnetic-Marking-Based Flow Metering with Optically Pumped Magnetometers. Applied Sciences. 2022; 12(3):1275. https://doi.org/10.3390/app12031275

[3] Vander H. W. R. et al., NMR applied to flow measurement, Instrumentation Technology, 53–58 (1968).

[4] KROHNE Messtechnik GmbH, Magnetic resonance multiphase flowmeter for the simultaneous measurement of oil, gas and water.