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Magnetic Flow Metering with Optically Pumped Magnetometers (OPM)

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Summary:

We present a novel non-invasive flow metering procedure where the flow velocity of a fluid is determined using polarized hydrogen nuclei of the fluid as magnetic markers. The metering procedure is based on a time-of-flight method in which magnetic information is applied to the liquid using a permanent magnet and a radiofrequency (RF) pulse. Downstream, the magnetic information is read-out by optically pumped magnetometers (OPM) by measuring the magnetic field produced by the hydrogen. We discuss results, application cases and challenges for industrial usability.

Keywords: Flow Metering, Magnetometry, OPM, ZULF-NMR, Time-Of-Flight Measurement

Introduction

Nuclear magnetic resonance (NMR) based flow metering has proven to be a viable tool for multiphase flow detection [1] with a range of industrial applications [1,2,3]. However, high-field NMR measuring devices are costly, show a high system integration effort and don't work with metallic pipes [4]. These aspects limit the methods applicability [5]. The recent commercialization of highly sensitive OPM [6] allowed us to develop a novel magnetic flow metering procedure in the zero-to-ultra-low-field (ZULF) regime [7]. The procedure allows flow detection through metal pipes, and, because the procedure does not require high magnetic fields, its implementation is effortless compared to the established high field NMR pendant [8]. The research presented is a continuation of the proof of principle for magnetic flow metering presented in [7]. As we continue to test the industrial potential of the procedure, we now analyze the viability of metering the flow of water flowing through industry standard steel pipes. In addition, a commercial electromagnetic flow meter is used to benchmark our flow metering results.

Materials and Methods

A schematic overview of the magnetic flow metering procedure is shown in Fig. 1. To determine the flow velocity of a fluid, polarized hydrogen atoms are magnetometrically monitored by OPM operating at nanotesla ambient field strength. The OPM have a sensitivity of <15 fT/Hz$^{0.5}$. In the presence of an external magnetic field, short resonance RF pulses change the fluids magnetic background, creating local magnetic marks. These marks are used as timestamps to perform a time-of-flight (TOF) measurement of the flow velocity.

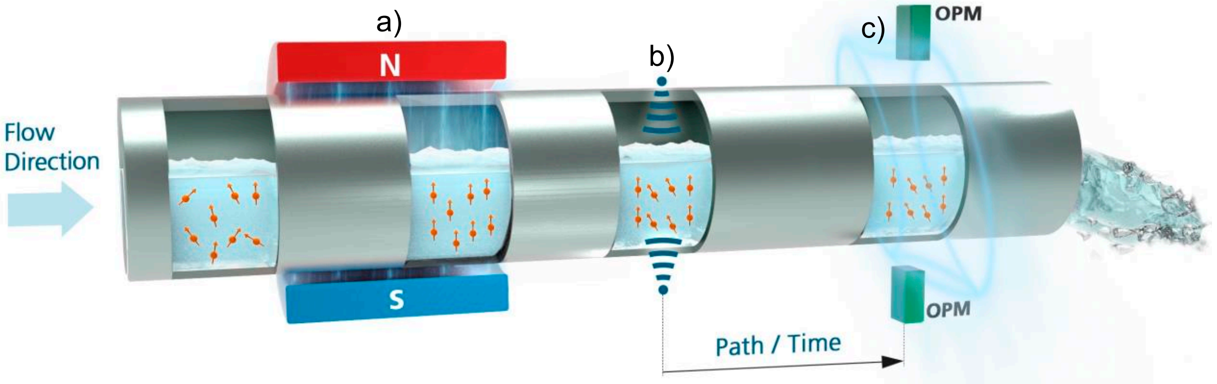

Fig. 1. Time-of-flight based measurement of a flow velocity. a) The fluid is magnetized by a strong magnet. b) A short and resonant RF pulse is applied to the fluid which creates a "notch" in a magnetized background. c) This notch is monitored by OPM downstream. The flow velocity is simply given by path over time where the timing information is given by the creation and detection of the notches.

To determine the flow velocity of the fluid we use the following relation:

$V=\Delta L/\Delta t$ (1),

Where ΔL is distance between the RF coil and the OPM. The timing information between pulse application and detecting its effect on the fluid polarization is given by Δt. The water is guided in a ½ inch stainless steel pipe. The results are compared to a commercial electromagnetic flow meter.

Results

The procedure was tested with tap water flowing at a constant velocity of 59 cm/s. The total measurement time was 10 min. Figure 2 shows an extract of the raw data used to determine Δt. The measurement results of the flow velocity detection are shown in Fig. 3. The average relative error of the magnetic flow metering apparatus is 0.5%. The commercial flowmeter showed an average relative error of 0.1%

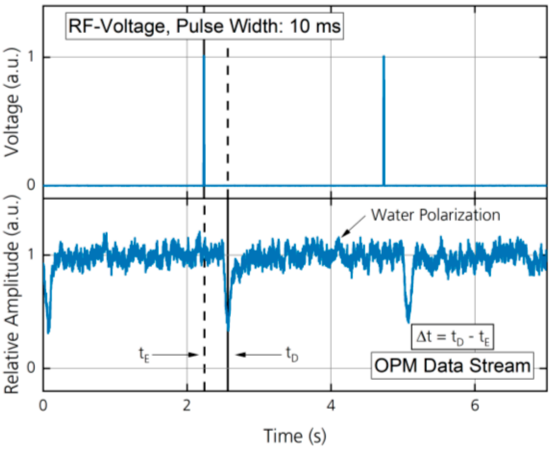

Fig. 2. Determination of Δt. The upper graph shows the voltage applied to the RF coil. Every 2.5 s a delta pulse is applied to the fluid. The lower graph displays the magnetic response of the fluid. After each pulse the water magnetic field is "marked". The relative position of pulse application and detection yields Δt.

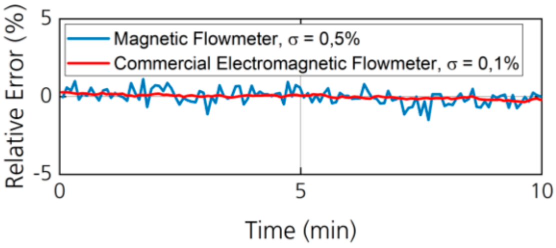

Fig. 3. Comparison of the flow velocity detected by the commercial electromagnetic flowmeter and the magnetic flow meter. The relative error of metering a constant flow velocity of 59 cm/s is plotted against the measurement time.

Conclusion and Outlook

The conducted experiment demonstrates a successful magnetic flow metering performed with industry standard steel pipes. The relative deviation of 0.5% when metering a flow rate of 59 cm/s with the current experimental setup shows the viability of magnetic flow metering in this configuration. Comparing the magnetic flowmeter's performance to the commercial flowmeter underlines this statement.

Further research on the magnetic flow metering procedure will address the signal preparation section. Potential use cases range from inline fill level detection to resolving a flow profile with limited two-phase resolution. As the procedure is also non-invasive, we aim for a clamp-on demonstrator.

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