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Entwicklung von MRT-Techniken zur 3D-Geschwindigkeitsmessung in porösen Medien

Development of MRI techniques for 3D velocity measurements in opaque porous media

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MRT, MRV, Magnetic Resonance Velocimetry, poröse Medien
MRI, MRV, Magnetic Resonance Velocimetry, porous media

Abstract

This study examines the capabilities of Magnetic Resonance Imaging (MRI) to measure the flow field inside and around porous media. Compared to optical measurement techniques, MRI does not require optical access to the flow field. 3D velocity data of the full flow field can be acquired in minutes using relatively simple experimental setups. The most critical design parameter in MRI experiments is the magnetic susceptibility of the materials. Similar to the refractive index in optical measurements, the magnetic susceptibility must be homogeneous inside the measured volume to achieve distortion-free data. This effect is particularly crucial for flows through porous media because of the relatively large interface area between fluid and matrix material. Since water is typically used in MRI experiments, the materials used for the porous matrix must be selected according to the magnetic susceptibility of water. In this study, it is shown that some of the commonly used plastic materials are applicable for these experiments. Finally, in a proof of concept experiment, it is shown that the entire flow field inside and around a plastic foam can be measured with MRI.

Introduction

Turbulent flows through porous media and over permeable walls are encountered in a wide range of problems. In particular, porous media have gained increased interest in technical applications such as heat exchangers and mixing devices. This progress can be partly led back to the expansion of innovative 3D additive manufacturing techniques which allow the fabrication of highly complex geometries such as foam-like structures. What has been missing so far is a reliable and inexpensive experimental technique to investigate the flow through these structures and allow a better insight into the flow field.
Optical measurement techniques are often not suitable for applications in porous media because of limited optical access to the flow field. Matching the refractive index of the flow media and a transparent porous matrix is cumbersome and not always feasible. Full-field flow measurements in porous media are therefore limited to fundamental experiments (Butscher et al. 2011).

A measurement technique that can overcome these problems is Magnetic Resonance Imaging (MRI). Formerly a medical imaging modality, MRI has recently found an increasing interest in the field of fluid mechanics. MRI can be used to acquire various flow properties, such as velocity, temperature, Reynolds stresses, and species concentration (Elkins & Alley 2007, Gladden & Sederman 2013). The measurement technique does not rely on optical access. Therefore, flow models can be fabricated with rapid prototyping techniques using opaque material. The applicability of MRI for flows through porous media was demonstrated in Onstad et al. (2010).

This project aims to develop a measurement routine for applied experiments in porous media using MRI. The flow medium of choice is water. At first, various plastic and metal materials were examined with regards to their magnetic susceptibility. Particularly in porous media, inconstancies in magnetic susceptibility between the porous matrix and fluid leads to distortion and cancelation of the MRI signal.

After these preliminary studies were successfully carried out, a proof of concept experiment was conducted. It is shown that the flow field in a porous matrix can be measured using MRI under the condition that the materials are correctly selected. The presentation at the meeting aims at the experimental challenges and the application of this technique for future problems in science and industry.

Background on MRI and MRI-compatibility

MRI is commonly associated with the medical examination of the cardiovascular system in humans. Velocity-encoded MRI, commonly known as phase contrast (PC) MRI, utilizes the sensitivity of the signal phase to motion (Markl et al. 2012). A linear relationship between fluid velocity and signal phase is achieved via specially designed magnetic field gradients. This technique provides a three-dimensional insight into the flow structure without requiring optical or physical access to the flow field (Fukushima 1999). The acquisitions can be performed in three dimensions, with data rates as high as 100,000 data points per second. On the downside, MRI requires a flow medium with non-zero nuclear spin, for example, the hydrogen protons in water, and places restrictions on the materials used in the MRI experiment.

An important parameter in describing the compatibility of materials used for MRI is the magnetic susceptibility (Wapler et al. 2014). This parameter indicates the degree of magnetization of a material in response to an applied magnetic field. At interfaces between materials of different magnetic susceptibility, the magnetic field is distorted. The imaging errors related to these distortions are commonly known as susceptibility artifacts (Schenck 1996).

Since water is typically the working fluid, all other materials used in the MRI experiment must have a similar magnetic susceptibility as the one of water. This requirement is particularly crucial for porous media since, in these experiments, a relatively large interface area exists between fluid and porous matrix.

Study on MRI-compatible porous media

First, this study examines the usability of common materials for MRI experiments in porous media. As representative plastic materials typically used in MRI experiments, Polymethylmethacrylate (PMMA), Polyamide (PA) and Polyoxymethylene (POM) were selected. Also, a Polyvinylchloride (PVC) sample was examined since this is the standard material for water pipes, hoses, and connectors that may be used in the flow circuit of the

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MRI experiment. Cylindrical samples were fabricated from all these materials. In addition, a Polyurethane (PU) foam sample was selected since technical porous media is often made of this material, for example filter foams.

For some applications, it might be interesting to investigate the flow around or through metal porous structures. Note that it would not be possible to measure inside this porous material due to electromagnetic shielding; however, the flow around these structures could be theoretically measured. A possible application could be heat transfer experiments in which a realistic heat transfer characteristic is to be achieved. Promising metal materials investigated here are Aluminum (Al), Copper (Cu), and stainless steel 1.4301 (V2A).

All plastic and metal materials, except for the PU foam, were investigated in the same experimental setup, which consists of an array of cylinders that are placed perpendicular to the main magnetic field of the MRI machine. All samples were surrounded by water during the MRI measurements.

The applied MRI sequence was a conventional gradient echo sequence typically used for MRV measurements. The receiver bandwidth used in this study was set to the lowest possible value. Note that the receiver bandwidth describes the time that is used to acquire the signal. For longer times, i.e., shorter bandwidths, errors due to inhomogeneous susceptibility accumulate and become more pronounced. The short bandwidth applied here represents the longest practicable receiver time, i.e., the worst case scenario regarding susceptibility errors. Consequently, materials that do not produce imaging errors in this experiment are suited for conventional MRV measurements without reservations.

The left column in Fig. 2 illustrates the distortions in the image magnitude caused by the different plastic materials. Note that the image magnitude represents the signal of the water in the acquired slice. Bright areas contain the signal of water while dark areas contain background noise. In addition to the water signal, the image contains spurious signals caused by imaging errors such as susceptibility artifacts. It can be seen that most plastic materials result in no or only minor imaging errors. PMMA, PA, POM, and PU appear as the best choice. Note that in the PU sample, air bubbles were trapped inside the foam which produced local susceptibility errors. The images containing the PVC samples exhibit small geometrical distortions that have a similar shape, as observed in Schenk (1996). Accordingly, materials like PVC are not entirely suited as a matrix material for MRI experiments in porous media. However, the affected area in the image is relatively small so that this material could be used for structures close to the imaged volume.

While the image magnitude illustrates the effect of geometrical distortions caused by susceptibility errors, it might not fully represent the errors in velocity-encoded MRI. As described in the previous section, the velocity information in these experiments is encoded in the image phase. The image phase is shown in the right column in Fig. 2. Note that in these MRI measurements, the image phase was encoded differently as compared to velocity-encoded MRI. The image phase was encoded such that the phase angle increases linearly in one direction. The stripe-like pattern observed in the images is a result of multiple phase rotations, i.e., multiple 2π. This type of encoding was selected since the evenly spaced pattern easily reveals any distortions in the image phase. While PMMA, PA, POM, and PU revealed almost no phase distortions, the images associated with PVC showed small errors close to the sample.

Figure 3 shows the results for the metal samples. In contrast to the plastic material, all investigated metal samples produced significant distortions which affected a relatively broad image region. The data from the affected regions is rendered unusable. The highest distortions are observed in the images associated with the V2A samples. Note that the type of stainless steel used here represents one of the most common alloys. The results may be different for other stainless steel alloys.

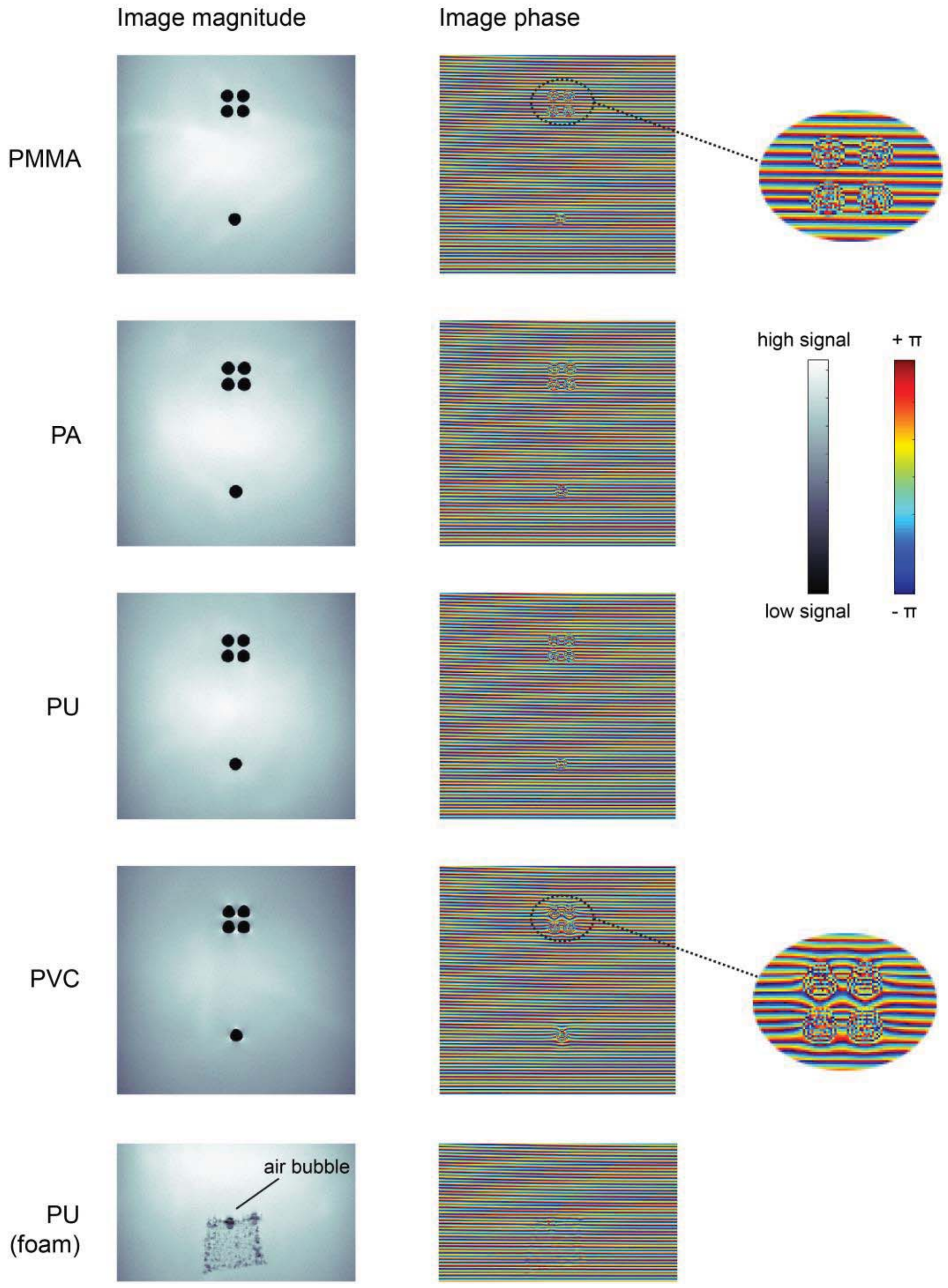

Fig. 2: Image magnitude and image phase of various plastic samples placed in water.

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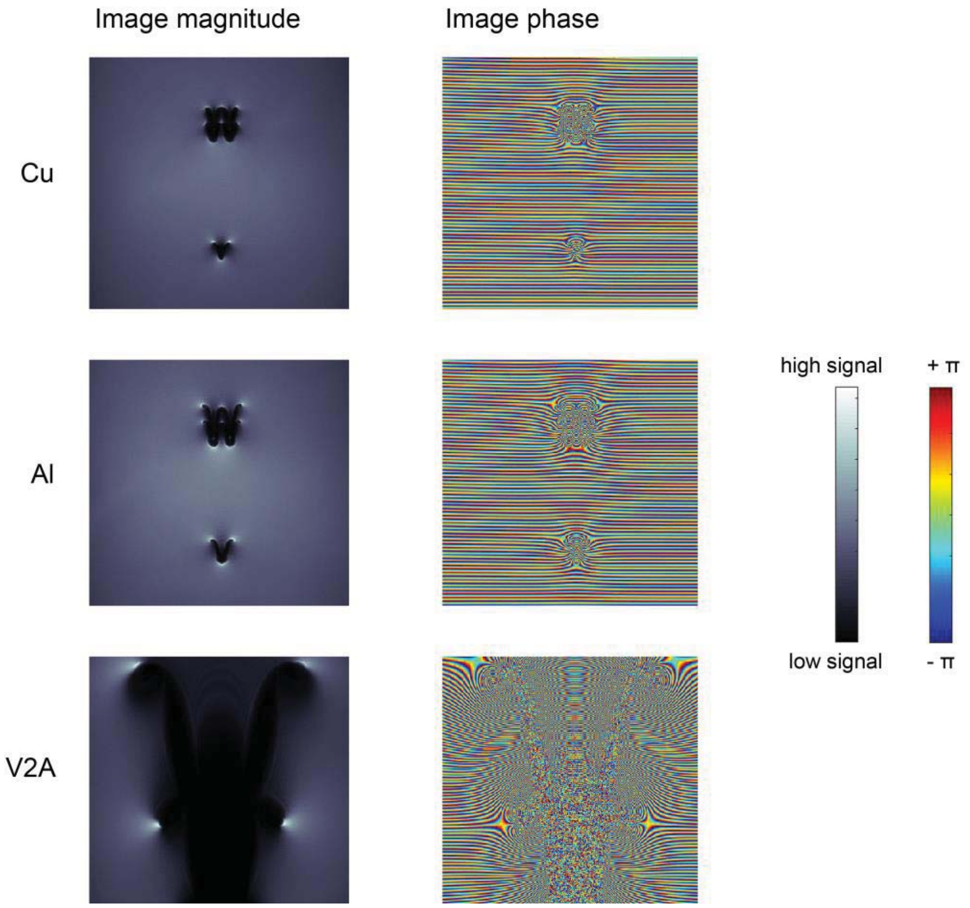

Fig. 3: Image magnitude and image phase of various metal samples placed in water.

Proof of Concept Study

After the effect of magnetic susceptibility was clearly shown in the previous section, an actual flow experiment was conducted to demonstrate the capabilities of MRI in porous media applications. The flow system shown in Fig. 4 consisted of a pipe with two tangential inlets on one side to produce a swirling motion. Downstream of this swirl generator, a filter foam made of PU was inserted into the pipe. This experiment represents a highly three-dimensional flow combined with a finely structured porous media. Optical measurements in this kind of setup would be cumbersome if not impossible.
Two examples of the processed image data are shown in Fig. 5. It is clearly shown that the flow field in and around the porous sample was measured with high quality. It was even possible to calculate streamlines through the porous sample, which proofs that the flow field through the interconnected pores of the foam was acquired without gaps.

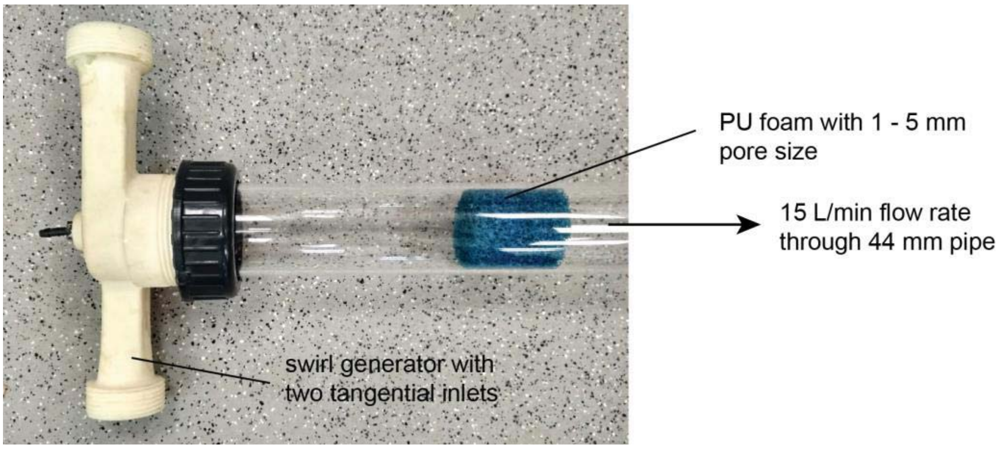

Fig. 4: Setup of the swirl flow experiment used in the proof of concept study.

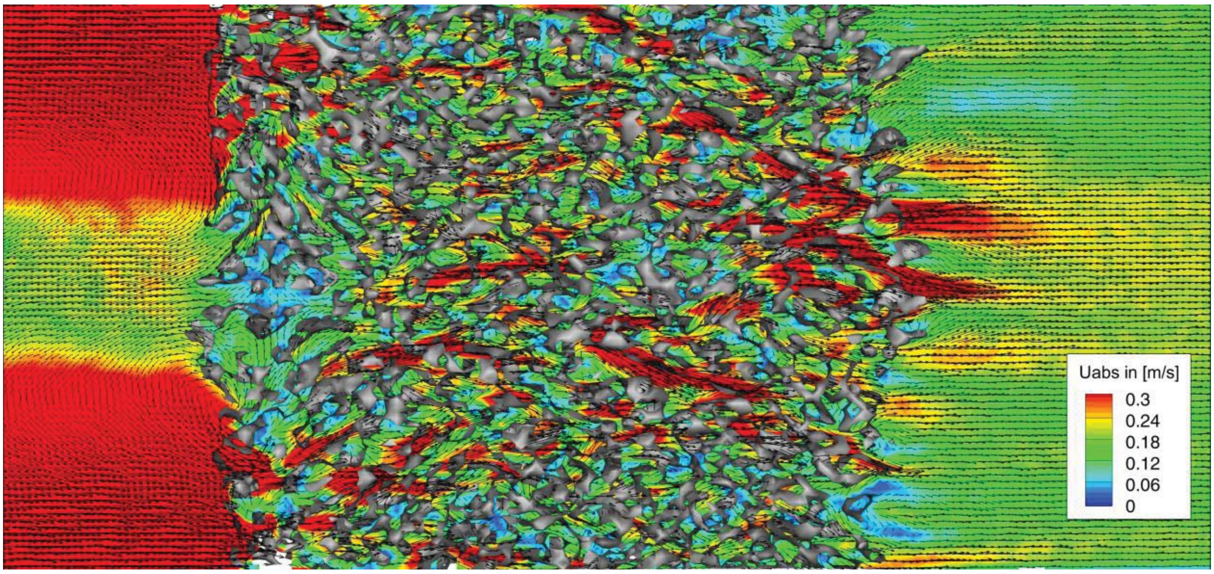

Fig. 5: Mid-plane cross-section of the 3D flow field in and around the porous media obtained from MRI.

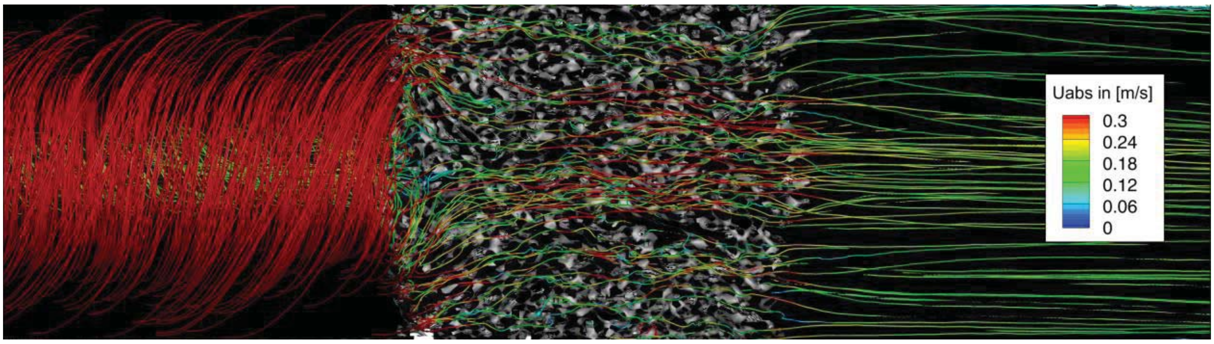

Fig. 6: Calculated streamlines in the 3D flow field in and around the porous media obtained from MRI.

Discussion and Conclusion

This study illustrated the capabilities of MRI for flow measurements in porous media. Compared to optical measurement techniques which require an entirely transparent material, the experimental challenges in MRI are different. The most decisive parameter is the magnetic susceptibility of the sample. Similar to the refractive index in optical experiments, the magnetic susceptibility must be homogeneous inside the measured volume to achieve distortion-free data.

Since water is typically used in MRI experiments, the porous media must be made of materials with similar magnetic susceptibility as the one of water. It was shown that some of the commonly used plastic materials are applicable for these experiments.

In conclusion, MRI allows relatively comprehensive but straightforward full-field velocity measurements in flows through porous media. Applications of this promising experimental technique can be found in various fields, for example in the design of heat exchangers and mixing devices.

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