Magnetic Resonance Imaging for Engineering Applications

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Magnetic Resonance Imaging (MRI) was originally invented for non-invasive diagnostics of human tissue. It is based on the nuclear magnetic resonance of hydrogen protons (also termed spins), which develop a precession motion with a fixed frequency (Proton Resonance Frequency – PRF) when exposed to an external magnetic field. In this state each spin can interact with electromagnetic fields that excite the spins and provoke a measureable reaction. By locally changing the magnetic field strength, the PRF can be altered in space, which makes it possible to acquire spatially resolved data. State-of-the-art MR scanners, consisting of a superconducting magnet, a magnetic gradient system and a radio-frequency unit, in combination with advanced imaging sequences make the acquisition (typically within minutes) of three-dimensional data sets fast and comfortable.

In the past years, more advanced MRI techniques have been developed. Most of them are based on phase contrast imaging, which utilizes the phase angle of the acquired complex magnetic resonance signal. One medical application is to measure the blood flow in the cardio vascular system. This technique is then termed Magnetic Resonance Velocimetry (MRV) and utilizes the magnetic gradient system to encode the signal phase with a velocity-dependent phase shift. The signal phase can also be sensitive to temperature changes. This is especially the case for water, which has a temperature-dependent chemical shift of the proton resonance frequency. This can be utilized to measure the fluid temperatures using the technique Magnetic Resonance Thermometry (MRT).

Transferring these advanced measurement techniques from medical diagnostics to engineering applications was the vision of a German researcher group in 2011, by implementing a close collaboration between engineers of the Technische Universität Darmstadt (Prof. Dr.-Ing. Sven Grundmann, now Professor at the University of Rostock, Department of Fluid Mechanics) and physicists of the University Medical Center Freiburg (PD Dr.
rer. nat. Bernd Jung, now team leader of the Department of Diagnostic, Intervention and Pediatric Radiology, University Hospital of Bern). Since then, a variety of MRI techniques for the acquisition of flow quantities, such as flow velocity, flow turbulence and flow temperature has been applied to technical flows, which shows the great potential as a measurement technique for engineering research and development. Due to the fact that no optical access is necessary, complex geometries and complex flows can be measured easily in a very short time without influencing the flow. During the past years many research projects have been conducted. Three important and successful projects are illustrated in the following.

**Using MRI to Help Making Aircraft Engines Better**

Modern aircraft engines operate at temperatures well above the melting point of their materials. A cooling system is required which usually features a combination of internal cooling ducts and external cooling holes. A prediction of the cooling effectiveness is difficult since the specific flow structure inside the cooling ducts is usually unknown. Most cooling designs are solely based on numerical simulations rather than measurements. Funded by the German Federal Ministry for Economic Affairs and Energy in cooperation with the aircraft engine manufacturer Rolls-Royce Deutschland, this study has been conducted with the aim to investigate whether MRI can be used to measure the flow field in such cooling ducts. The presented work discusses the applicability, the accuracy and uncertainty of MRI. The investigated flow systems are generic and feature a strongly turbulent swirling flow as a demanding test case. The mean flow field is measured via MRV using water as flow medium while all important dimensionless quantities are kept similar to the real application. The results are compared to state-of-the-art laser measurements and sophisticated numerical simulations. As the main outcome, it is shown that the measured flows are significantly different to what has been predicted by conventional design tools. Furthermore, the measurements generated a better understanding of the flow sensitivity and new design criteria could be deducted. MRV has been proven a valuable supplement to existing tools in jet
Applying MRI Techniques in Internal Combustion Engine Geometries

Magnetic Resonance Velocimetry was applied to acquire three-dimensional three-component (3D3C) intake flow velocity data for a modern engine geometry. MRV is especially beneficial in this application because it resolves the volumetric flow within the complex internal system of the intake port for which optical access is limited for traditional velocimetry methods. The measurements were performed in an engine-equivalent polyamide model with 1:1 scale geometry of a single-cylinder direct injection spark-ignition optical engine, shown in Fig. 2.

Using MRV, zones of recirculating mass flow in the inlet port and around the periphery of the valve curtain could be identified in 3D space. Reducing the effective cross-sectional area for cylinder-filling, these recirculation zones may cause losses in volumetric efficiency and possibly contribute to cyclic variations in internal combustion engines. The MRV measurements quantitatively resolved a highly uneven distribution of the mass flow discharging into the cylinder through the valve curtain (annular area between the valve head and valve seat).

The MRV-measurements were validated with PIV-measurements, conducted in the original engine which features optical access. Despite a number of differences in operating parameters the validation showed excellent agreement of the flow fields for MRV and PIV. MRV-measurements can be of beneficial use for technical flows as they allow for a new perspective of flow-characterization.

Magnetic Resonance Thermometry for Heat Exchangers

Measuring the three-dimensional temperature field (MRT) in combination with the three-dimensional three-component velocity field (MRV) in one experimental setup was the goal of this “Deutsche Forschungsgesellschaft”-funded joint research project.

This work aimed to apply the novel MRT technique to investigate the temperature and velocity distributions in simple heat exchangers, such as a countercurrent double pipe and a generic pin fin array. In order to do so, the flow models have to be designed to meet the requirements given by the very sensitive MRT technique. A typical experimental setup with all components necessary for a MRT measurement is shown in Fig. 3.

The results of the MRT and MRV measurements for the double pipe heat exchanger reveal a three-dimensional temperature structure in combination with the development of strong secondary flows which is shown in Fig. 4. Such a behavior is obvious for a mixed convection flow, which is a combination of flow driven by buoyancy forces due to the presence of temperature-induced density differences and flow driven by the streamwise (Z-direction) pressure gradient provided by the pump. The capability to measure the temperature distribution and velocity field in
one setup with high spatial resolution helps to gain new insights into complex heat transfer processes, especially where mixed convection takes place and temperatures and velocities influence each other significantly. This makes this measurement technique very valuable for the field of thermofluid sciences.

**Summary and Outlook**

MRI is fast, efficient and versatile. In addition to the broad portfolio already used in medicine, it is an applicable measurement technique for fluid mechanics, thermodynamics and chemical engineers. MRI is superior to other conventional measurement techniques where a three-dimensional view is necessary for the understanding. The only requirements are an MR machine and a flow setup. A scanner which is exclusively used for engineering research is the goal of Prof. Sven Grundmann at the University of Rostock. This will make MRI available for a great part of engineers in the near future.

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