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MRV Geschwindigkeits- und Turbulenzquantifizierung im MATiS-H Benchmark zur Validierung von CFD-Methoden der nuklearen Reaktorsicherheit

MRV velocity and turbulence quantification in the MATiS-H Benchmark for validation of CFD methods in nuclear reactor safety studies

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Zusammenfassung

In dieser Studie wird der Einsatz der Magnetresonanzvelocimetrie (MRV) zur Validierung numerischer Strömungssimulation (CFD) in Reaktorsicherheitsstudien gezeigt. Im Gegensatz zu optischen Messverfahren ermöglicht die MRV eine vergleichsweise einfache Erfassung des Strömungsfeldes auch in den inneren Unterkanalebenen eines Brennstabbündelmodels. Die Messtechnik ist deshalb eine vielversprechende Methode um umfassende Daten zur Validierung der in der Reaktorsicherheit genutzten CFD-Methoden bereitzustellen. Zu diesem Zweck wurde eine MRV-kompatible Nachbildung des MATiS-H Benchmark errichtet und das Geschwindigkeitsfeld sowie der Reynoldsspannungstensor gemessen. Der Versuchsaufbau ist ein leicht vergrößertes, maßstabsgetreues Modell eines Druckwasserreaktors mit 5x5 Brennelementen und einem ‚swirl-type‘ Abstandshalter stromaufwärts des Messbereichs. Mit der erfolgreichen Inbetriebnahme der Versuchsanlage ist das langfristige Ziel eine umfassende Datenbank für die Validierung von CFD-Methoden der Reaktorsicherheit aufzubauen und Industriepartnern zur Verfügung zu stellen. Der Vortrag auf der Konferenz wird außerdem auf den Vergleich mit den in der Benchmark-Studie veröffentlichten LDV-Daten eingehen sowie die Möglichkeiten und Grenzen der 3D-Validierung numerischer Methoden unter Verwendung der MRV-Daten diskutieren.

Summary

This study shows the use of MRV to support the validation of Computational Fluid Dynamics (CFD) in nuclear reactor safety studies. In contrast to optical measurements, MRV allows acquiring fluid mechanics data even in the inner sub-channels of a rod bundle model. The measurement technique is, therefore, a promising method to provide comprehensive data for the validation of CFD methods in reactor safety. For this purpose, an MRV-compatible replica of the MATiS-H test facility was constructed, and velocity vectors and Reynolds stress tensors were measured. The benchmark represents a scaled 5x5-fuel assembly model of a

pressurized water reactor with a ‘swirl-type’ mixing device upstream of the measurement region. Following this successful commission of the test facility, ongoing work is now dedicated to providing a detailed experimental database for comprehensively validating CFD methods in reactor safety. The presentation at the conference will also discuss the data quality compared to the LDV data published in the benchmark study, as well as the possibilities and the limitations of 3D validation of numerical Methods using the MRV data.

Introduction

Nuclear reactor safety studies are mainly based on computational fluid dynamics (CFD), and there is an enormous interest in evaluating the ability of different CFD methods to predict the flow field inside the reactor core. For this reason, the nuclear energy agency (NEA), as a part of the organization for economic cooperation and development (OECD) and the Korea atomic energy research institute (KAERI), proposed a benchmark to compare state-of-the-art CFD methods used by different research groups (Smith et al., 2013).

The benchmark is based on the cold loop test facility MATiS-H (Measurement and Analysis of Turbulent Mixing in Subchannels-Horizontal) at KAERI. It consists of a square channel with 5x5 rods replicating a fuel rod bundle section inside a pressurized water reactor (PWR). In these reactors, water under high-pressure flows through the fuel rod bundle to dissipate the generated heat. Spacer grids with mixing devices are installed between the rod bundles to improve heat transport. For the benchmark, two spacer grids with different mixing vane designs were proposed, representing a ‘swirl-type’ spacer grid and a ‘split-type’ spacer grid, respectively.

At the MATiS-H test facility, laser Doppler velocimetry (LDV) measurements were performed to provide experimental validation data for the CFD study (Chang et al., 2014). The lateral velocity was measured in 1/8 of the flow field at four positions downstream of the spacer. The measurement window was located at the end of the more than 4 m long test channel to provide visual access for the LDV measurement. The installed spacer grid was movable to adjust the distance to the measurement plane. For the axial velocity, measurements were only possible in the gaps between the rod rows. This illustrates the experimental effort required for LDV measurements in such complex structures. At the same time, data can still not be recorded from the entire flow field inside the fuel bundle model.

In contrast, MRV enables comparatively fast and three-dimensional velocity vector measurements even in opaque structures such as the MATiS-H benchmark. It only requires that the flow medium has a high density of measurable protons, and the other materials used inside the measurement region have little effect on the magnetic field. For example, metal parts should be avoided, and water is a suitable flow medium for common MRI scanners.

Previous studies used MRV to capture quantitative velocity data in rod bundle configurations. For example, Bruschewski et al. 2020 and Oliveria et al. 2021 investigated different types of deformation to demonstrate the benefit of MRV for reactor safety studies. Bruschewski et al. 2021 measured the flow behind a spacer grid based on an industrially used design of the Framatome GmbH (Erlangen, Germany) and compared it to CFD. They applied an automatic three-dimensional data matching of experimental and numerical results to show how MRV can be used in the assessment of CFD methods.

Moreover, recent studies showed that MRV could also capture the Reynolds stress tensor in turbulent flows. Measurements in technical benchmarks such as the periodic hill channel (Schmidt et al., 2020) and the benchmark nozzle of the U.S. Food and Drug Administration (John et al., 2022) showed high qualitative agreement with optical methods. Systematic errors in the MRV were reported that resulted in quantitative differences, but sources of errors have been identified, and methods to compress them are part of ongoing studies.

This study aims to install an MRV-compatible replica of the MATiS-H benchmark. The experiments are designed as similar as possible to the benchmark study to allow for a comparison with the previously published LDV results. The long-term aim is to establish MRV as a reliable method to provide CFD-grade measurement data that allows for a three-dimensional validation of numerical methods.

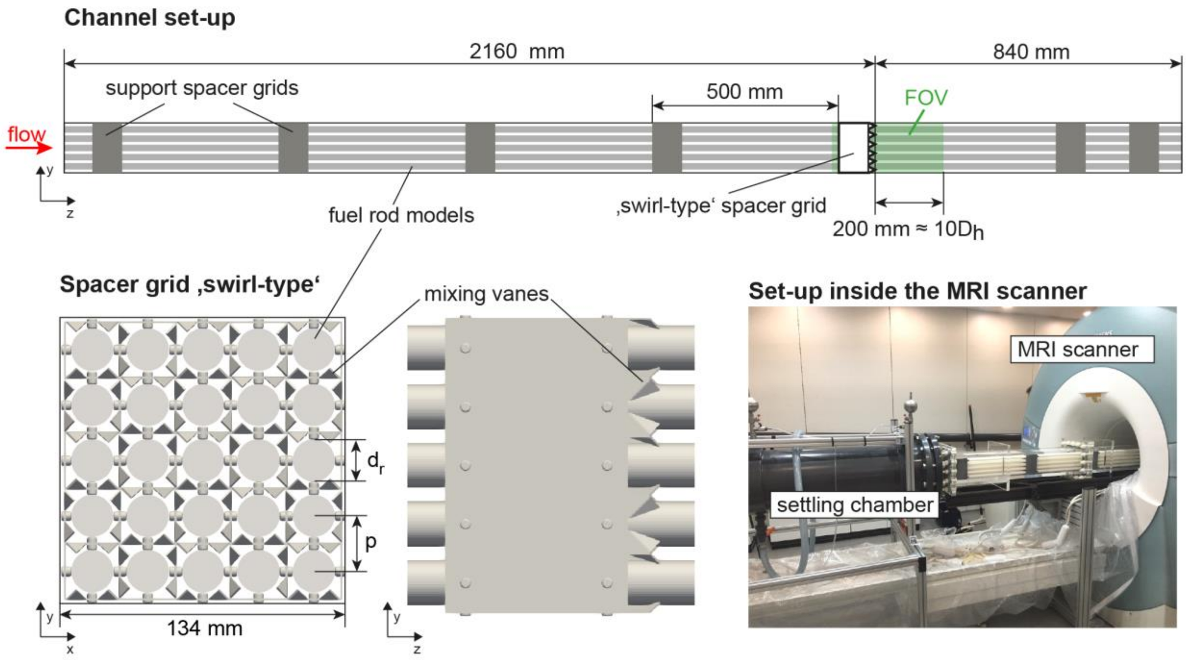


Figure 1: Overview of the rod bundle model

Material and methods

MRV Measurements are performed at the MRI flow lab, which is part of the Institute for Fluid mechanics at the University of Rostock. It is equipped with a 3T whole-body MRI-Scanner (Magnetom Trio, Siemens, Erlangen) and is exclusively used for experimental fluid mechanics. Furthermore, it includes a permanently installed pump system with a 1000 L water reservoir and a maximum flow rate of 1500 l/min. This flow system is connected to a settling chamber followed by a 3 m channel made from acrylic glass (PMMA) in which the rod bundle with the ‘swirl-type’ spacer grid is installed. The design of the set-up and the position of the measurement area (Field of view, FOV) are displayed in fig. 1.

In contrast to the set-up described in Chang et al. 2014, no metal parts are used inside the channel. The rods are made from grounded Polyoxymethylene (POM) as the magnetic susceptibility of POM is close to the one of water. This minimizes systematic errors in the MRV measurement (Wapler et al., 2014). As POM is less rigid than stainless steel, additional support spacer grids without mixing devices are installed to prevent the rods from bending. The spacer grids are additively manufactured using Multi Jet Fusion with a wall mean roughness of 11 µm and a standard accuracy of ±0.3%. The design of the ‘swirl-type’ spacer used in this study was adopted as proposed by Smith et al. 2013.

In the MATiS-H test facility, the rod bundle was 2.6 times larger compared to the dimensions of a realistic fuel rod bundle. For the MRV-compatible set-up designed for this study, the scaling factor was set to 2.0 to reach a compromise between relative resolution, flow rate, and maximum velocity. This results in a rod diameter (d_r) of 20 mm, a hydraulic diameter (d_h)

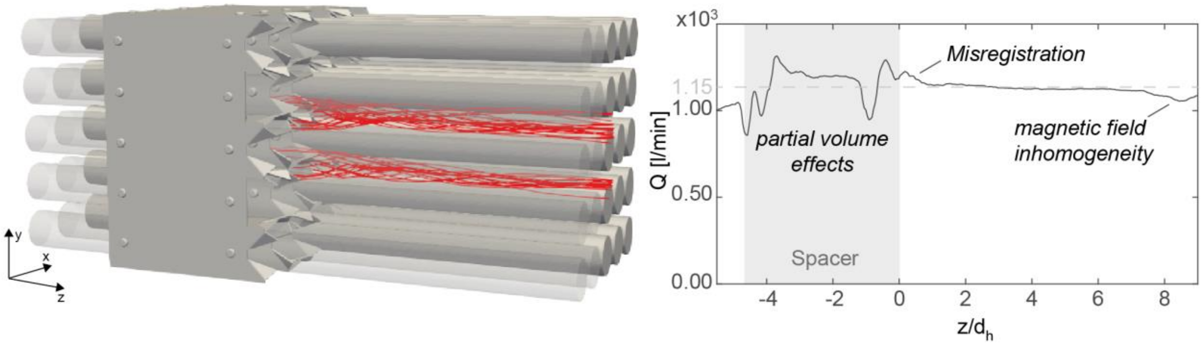
of 19.18 mm, and a pitch (p) of 26.71 mm. The flow medium was water with copper sulfate (CuSO4) added as a contrast agent to accelerate the measurements. During the measurements, the pressure was 0.3 bar, and the fluid temperature was 35°C. The flow rate was set to 1150 L/min to reach a Reynolds number of 50,250 as proposed in the MATiS-H benchmark.

The velocity field was captured with 0.9 mm isotropic resolution in a three-dimensional volume reaching from $1d_h$ upstream of the spacer to $10d_h$ behind. Additionally, Reynolds stress tensor was measured $1d_h$ and $4d_h$ downstream of the spacer. These positions are similar to the PIV measurements performed by Chang et al. 2014. The slice thickness is 5 mm, and the in-plane resolution is 1.0 mm. Velocity measurements are performed using the 4D flow method proposed by Markl et al. 2012 with an optimized gradient design described by Schmidt et al. 2020. The Reynolds stress tensor is captured using ICOSA6 encoding as described in Schmidt et al. 2021.

Results

Figure 2 illustrates the results of the three-dimensional velocity vector **u** = {u v w} measurements. For the post-processing, the same routines as for CFD analysis can be used. For example, streamlines are computed inside selected sub-channels, as shown in fig. 2a. Furthermore, the flow rate Q can be calculated (see fig. 2b), which helps to indicate the influence of systematic errors in MRV. Inside the spacer grid, segmentation between fluid volume and spacer material gets inaccurate as many voxels cover a mixture of fluid and wall, known as the partial volume effect. Furthermore, flow-induced displacement, often referred to as misregistration, becomes visible in areas of strong acceleration, such as at the end of the spacer. Deviations at the outer edges arise from the rising magnetic field inhomogeneity.

The streamlines indicate swirls formed by the spacer grid, which are either left or right rotating, depending on the mixing vanes orientation. As described by Chang et al. 2014, at $1d_h$, these circular swirls rotate around the sub-channel center with low flow between the sub-channels. With further distance to the spacer, the swirls decay, and the cross-flow between the sub-channels increases. These flow characteristics can also be observed in the MRV results presented in fig. 3. Here, the absolute velocities at $1d_h$ and $10d_h$ behind the spacer grid are shown. Additionally, every third lateral velocity vector is displayed in the enlarged sub-channel.


a) Selected streamlines from 3D MRV

b) Flow rate and error identification

Figure 2: Results from 3D measurements, a) calculated Streamlines in two selected sub-channels, and b) calculated flow rate indicates the influence of systematic errors.

Figure 4 shows the turbulent kinetic energy k calculated from the measured RST normal stresses at $1d_h$ and $4d_h$ behind the spacer. It can be seen that the turbulence decreases with further distance to the spacer grid, which was also described by Chang et al. 2014. As the mixing vane configuration is either left or right rotating, the distribution of k varies between the sub-channels close behind the spacer grid. However, variations in the maximum values of k may also indicate an influence of systematic errors. In the 2D RST measurement method, one of the lateral components is more prone to flow-induced errors. This causes an overestimation of k when this component is significant. With decreased lateral velocities, the influence of these flow-induced errors is reduced. At 4dh, the distribution and maximal values of k become more similar in all sub-channels.

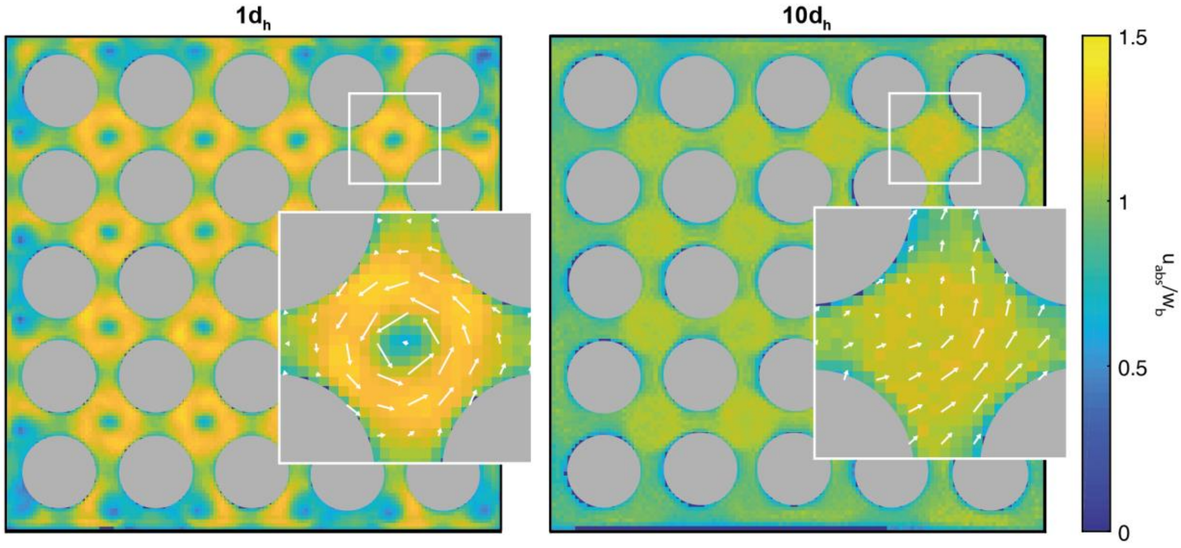


Figure 2: Absolut velocity u_{abs} at $1d_h$ and $4d_h$ behind the ‘swirl-type’ spacer grid. Additionally, lateral velocity vectors $\mathbf{u}_{lat}$ = {u v} are displayed as white arrows for an enlarged sub-channel.

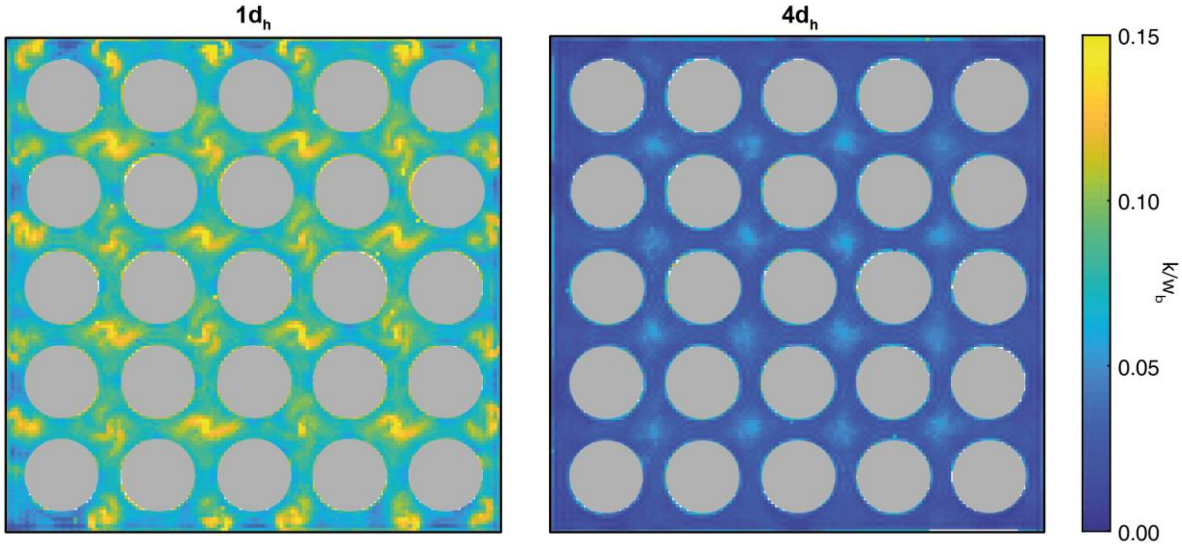


Figure 3: Turbulent kinetic energy k calculated from the RST normal stresses measured $1d_h$ and $4d_h$ behind the ‘swirl-type’ spacer grid.

Discussion and outlook

This study showed how MRV could be used to provide validation data for benchmark cases to support nuclear reactor safety. Comprehensive datasets of the three-dimensional velocity vector and two-dimensional RST were measured in the entire flow volume of the MATiS-H benchmark test. The MRV data compare well with the LDV results published by Chang et al. 2014. The main advantage of MRV is that data are generated for regions that are not accessible by optical measurement methods.
In the ongoing measurement campaign, detailed experimental data sets are generated, and varying spacer grid designs will be implemented. Furthermore, new MRV methods will be applied to minimize the effects of flow-induced systematic errors, especially when quantifying the RST. The data will be used by the industry to calibrate and validate their CFD methods and will be provided in an experimental database for the comprehensive validation of CFD methods in reactor safety.

Acknowledgments

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