Improved Magnetic Resonance Velocimetry to Acquire Velocity and Turbulence Statistics for Nuclear Reactor Safety Problems

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Magnetic resonance velocimetry (MRV) is a comparatively new measurement method in experimental fluid dynamics, which neither requires visual or physical access to the flow field nor tracer particles. In recent years, nuclear reactor safety (NRS) problems have been identified as an application that could greatly benefit from this measurement technique. In particular, MRV can provide comprehensive experimental data of the mean velocity and turbulence statistics for validating computational fluid dynamic (CFD) methods used to predict the flow field in the fuel assemblies of pressurized water reactors (PWR).

These reactors are the most common design for nuclear power plants today. Inside the reactor core, the nuclear material is stored as pellets in rods surrounded by cladding. Cooling the fuel rods is required to dissipate the heat emitted from nuclear fission for power generation, but it is also crucial for the safe operation of the reactor. Insufficient cooling may result in the destruction of the cladding and the emission of radioactive radiation. Therefore, detailed knowledge of the flow field inside the reactor core is essential to understand the mixing of the coolant and, thus, maintain the safe operation of the power plant. The fuel rods are supported by spacer grids equipped with vanes to increase the mixing of the coolant, thereby optimizing the heat transfer. In the OECD/NEA-KAERI benchmark, a 5x5 fuel assembly and two generic designs of spacer grids were proposed to investigate the reliability of CFD methods. The considered flow is single-phase and isothermal at ambient conditions. The Reynolds number is 50,250, related to the hydraulic diameter. Experimental reference data to evaluate the numerical results were provided from laser Doppler velocimetry.

In this thesis, an MRV-compatible replica of this benchmark is installed to acquire the time-averaged flow field using MRV. Two aspects are the objective of this work. The first is to strengthen the position of this measurement method in industrial-relevant applications. The measurements in a well-known benchmark with reference data available for comparison demonstrate the reliability of MRV. However, to achieve this, the essential objective is to enhance MRV to quantify the flow parameters in these applications accurately. Strong velocity gradients and higher orders of motion, such as acceleration, characterize the flow behind the spacer grid. It is known from previous studies that this causes substantial errors, especially in MRV turbulence quantification, which only a few studies have used for technical flows. The identification and reduction of errors are needed to use MRV for 'CFD-grade experiments' as defined by the Nuclear Energy Agency (NEA).

Measurements of the mean velocity vector are performed in a 3D volume from upstream of the spacer grid up to 10 times the hydraulic diameter behind. The entire cross-section of the fuel assembly is captured, including the boundary layers within the discretization limits of the spatial resolution. This results in more than 2 million velocity vectors acquired within a few hours. Additionally, all six components of the Reynolds stress tensor are quantified in several 2D slices. The first measurements were conducted with a previously validated imaging routine. As it was expected, the results are strongly affected by flow-induced errors. Afterward, measurements are performed with an improved imaging technique, yielding a significantly increased accuracy. Both measurement campaigns and the analysis of all sources of errors are presented in detail.

Finally, the results are compared to the initial benchmark study. The results of MRV and LDV are in excellent agreement if the improved MRV is used. Moreover, MRV measurements can solve the major issues reported in the initial benchmark study. On the one hand, much simpler outlet conditions are realized in the experimental setup as MRV does not need optical access to the flow field. On the other hand, it was reported that the ranking of the CFD methods depended on the amount of data used for comparison, for example, 1D velocity profiles or 2D data from an entire subchannel. With MRV, a 3D full-field validation of the numerical results would be possible.

In summary, this thesis successfully improved MRV to quantify mean velocity and turbulence statistics for NRS problems accurately. These achievements will strengthen MRV as a reliable measurement technique in experimental fluid mechanics.