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MRI as a tool for nuclear safety

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Objectives

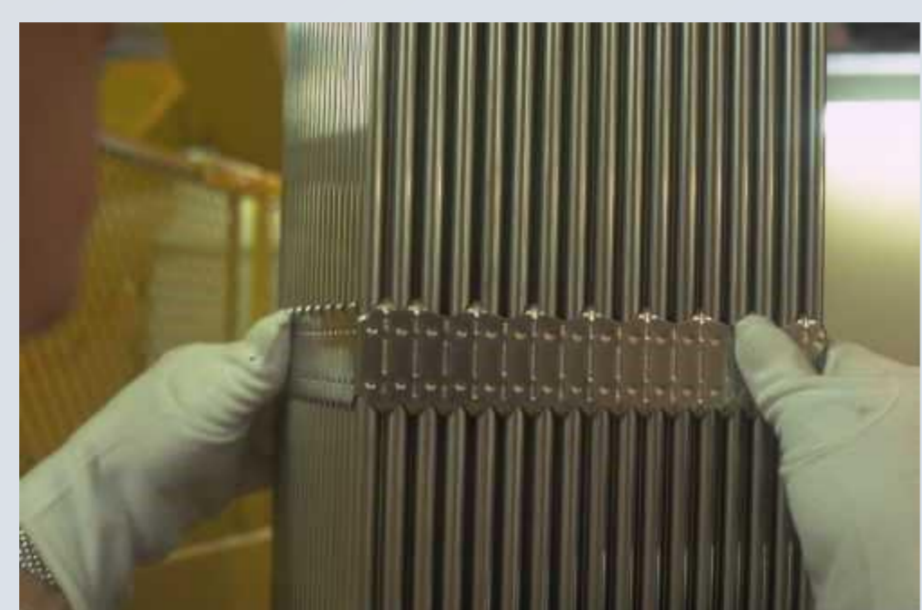
The loss of coolant accident (LOCA) is one of the most dangerous failure that could happen in a nuclear reactor. It was notably the cause of the Fukushima Daiichi disaster in 2011. Even if the power plant operator is able to reflood the fuel rods after the failure in order to cool them, the water will instantly evaporate and the cooling flow will be diphasic (liquid/gas), less effective than a purely liquid flow. Moreover, the fuel rods cladding can swell due to the intense heat, and this can block the circulating channels and modify the flow distribution.

We used MRI velocimetry to visualize such phenomena, as classical (optical) velocimetry techniques are unable to image through these opaque systems.

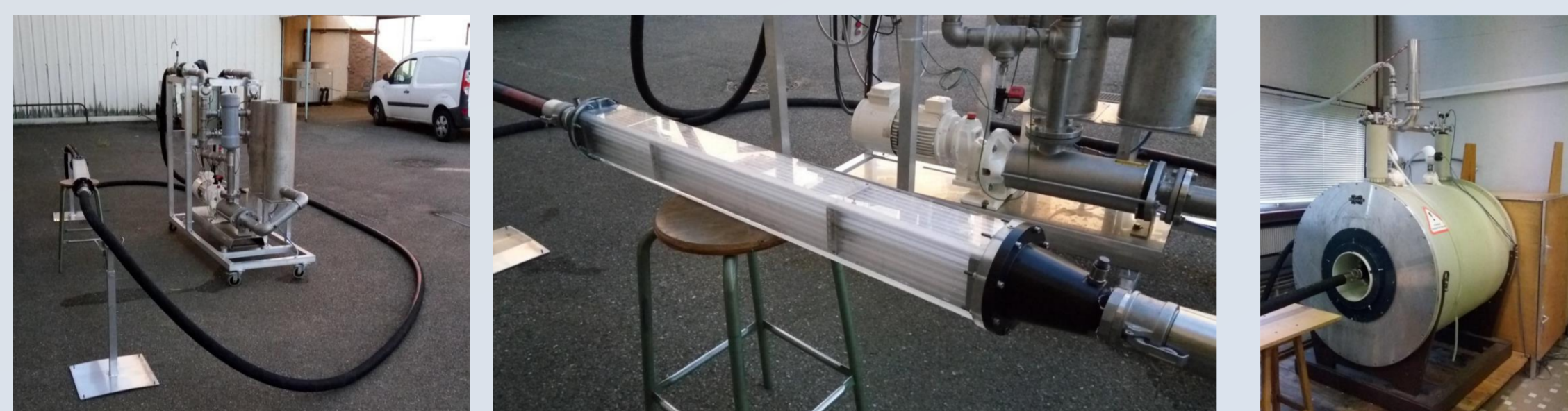
Monophasic flow in a 7*7 rods bundle

Experimental setup

The goal is to observe high velocity (up to a few m/s) flow in a bundle of rods swelled by the heating. The bundle is made of 3D printed plastic rods with a length of 1m and a swelled area of 10 to 50 cm in the middle. Various swelling were studied.



Real Nuclear Fuel rods assembly



Pump and pipes setup

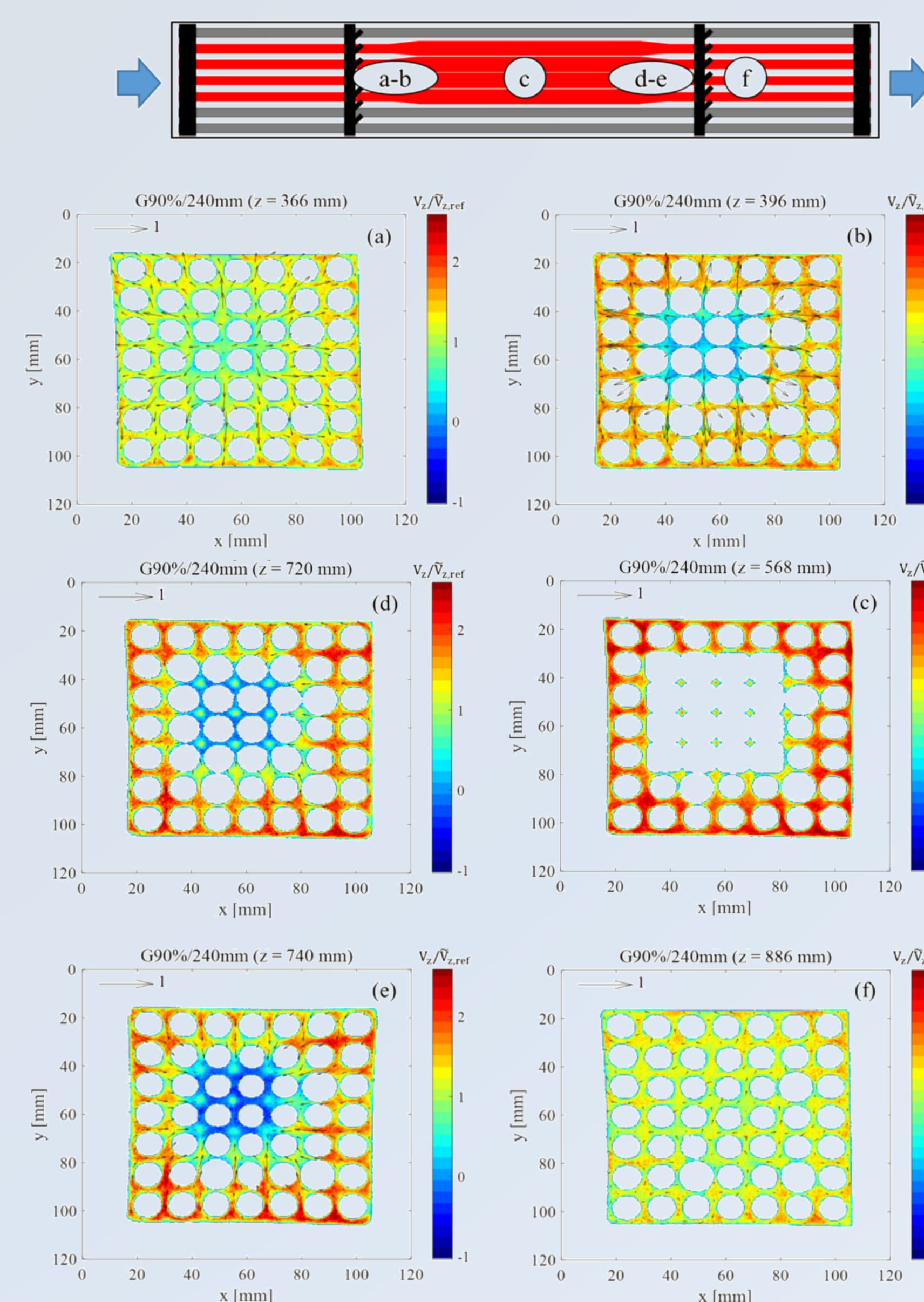
7*7 rods assembly in the plastic case

Setup in the MRI

The rods are assembled in a 12*12*120 cm rectangular plastic case, with pipes entering et exiting the case. A progressive cavity pump allows us to reach flows up to 250 L/min. There are two buffer water tanks in the setup in order to stabilize the flow. Some differential pressure sensors were added for safety, as the pump is automatically stopped in case of pressure drop.

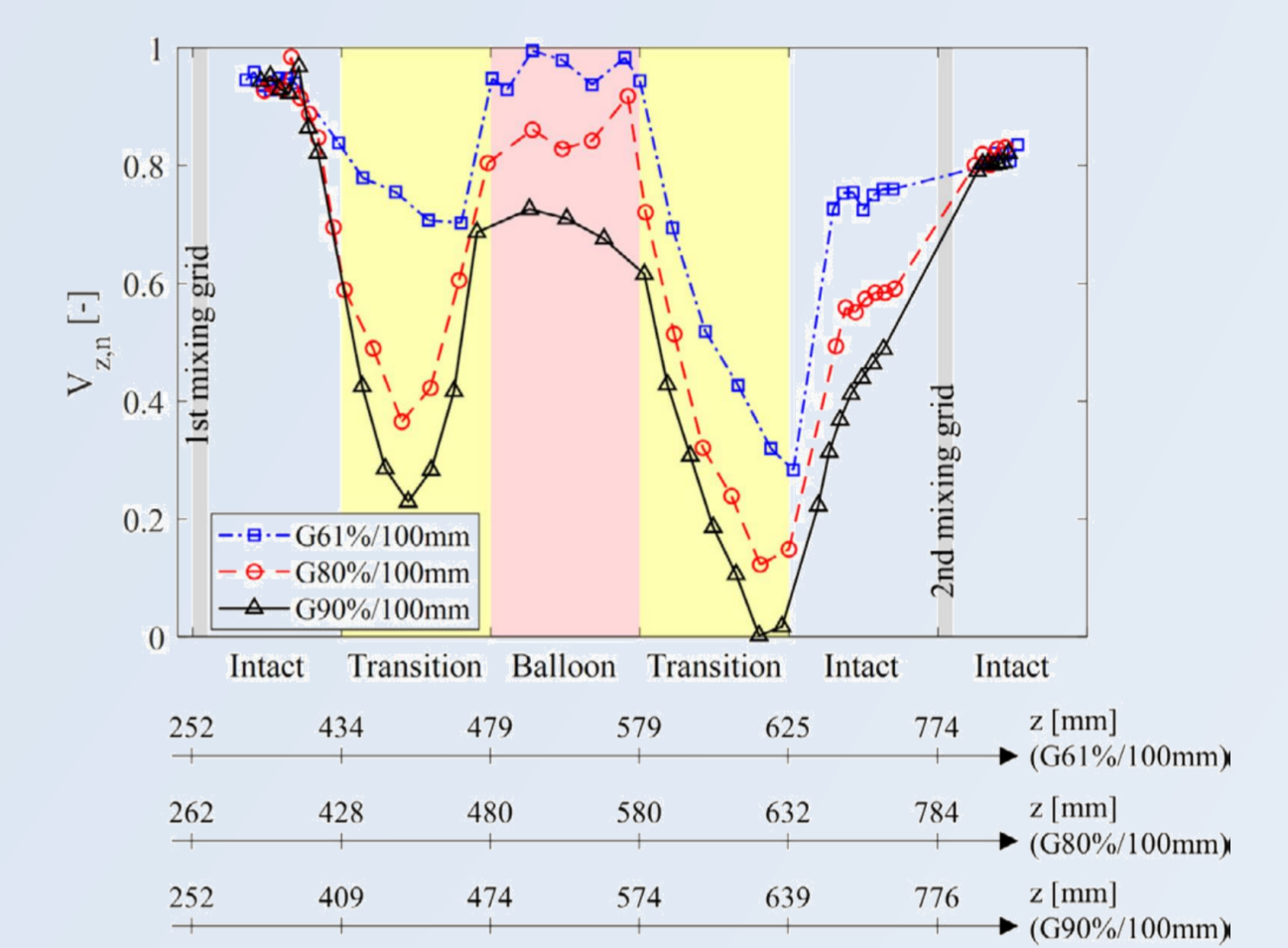
Experiments were carried out in a Bruker Biospec 24/40, using a 16 cm diameter volume resonator.

Due to the high flow rates, spin echo experiments were not usable. We therefore used Gradient Echo with bipolar pulses imaging sequences



Velocity fields with a swelled bundle

Results



Axial velocities at different positions and for various swelling

Different combinations of velocities and swelling were tested. The main results are the following :

- Flow velocities are (much) higher outside the swelled area. There is no “acceleration” effect inside the deformed area. This leads to a less effective cooling after a LOCA
 - There is some flow recirculation (backward flow) just after the swelled area, again leading to a lesser efficiency of the cooling.
- These images were used to verify and calibrate computer numerical simulation codes (e.g. DRACCAR simulation code from EDF/IRSN)

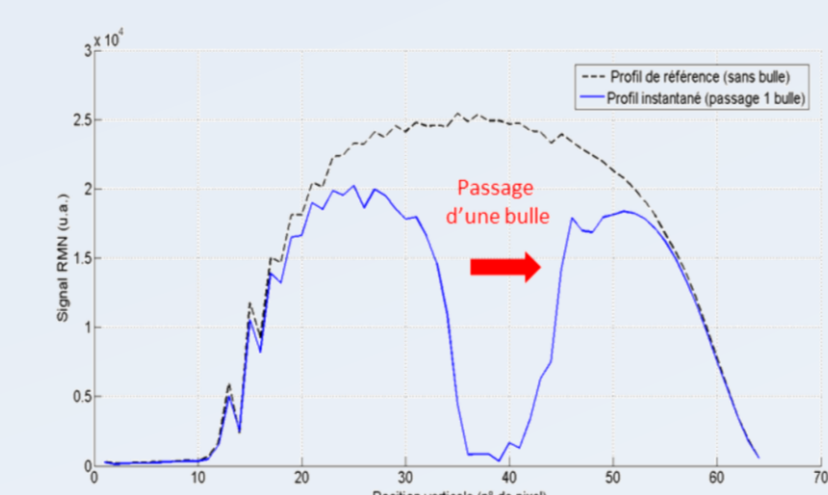
Air/water diphasic flow

Setup

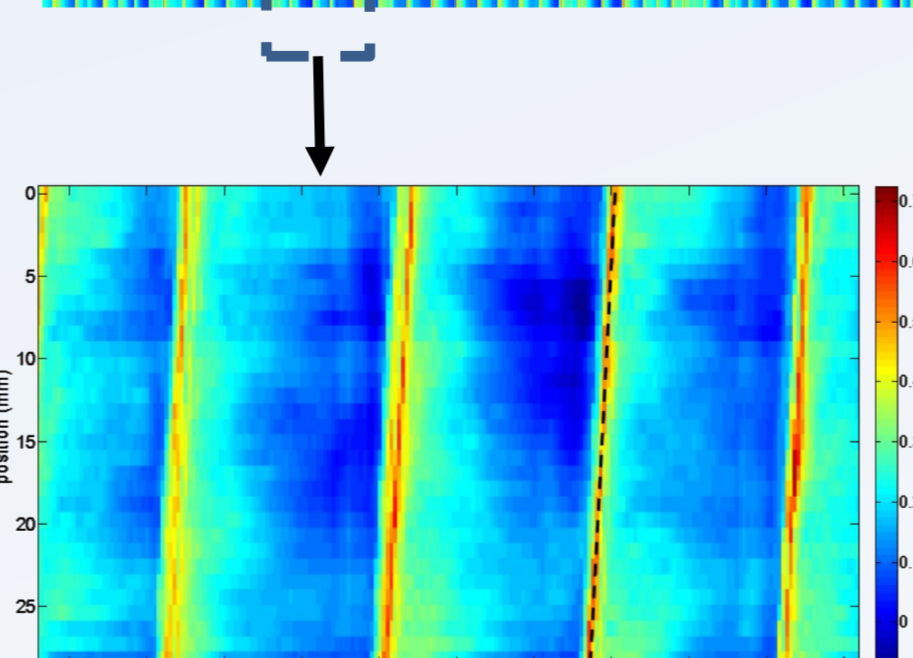
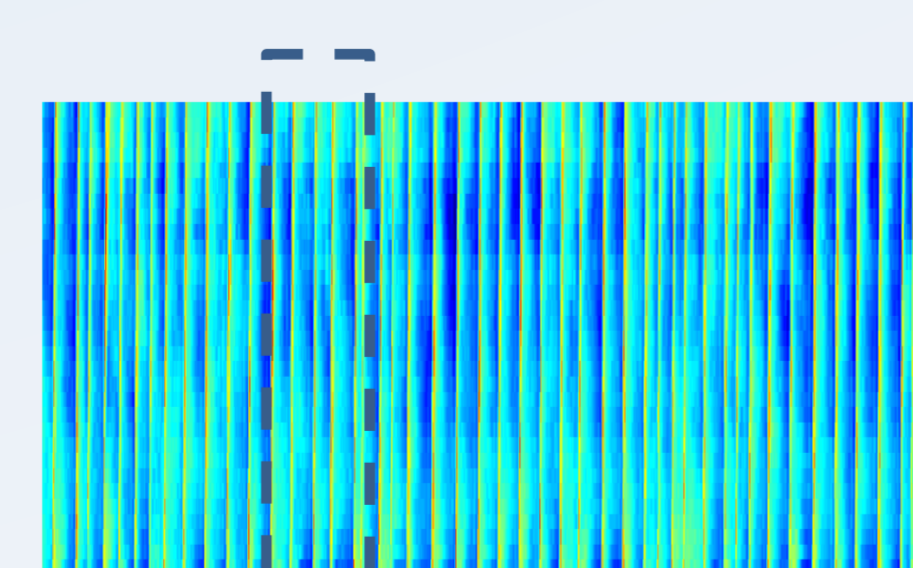
The setup is close to the previous one, but with a vertical flow inside a cylindrical cavity with or without plastic rods, with a section of 28 mm. The setup is inserted in a Bruker Avance III 600 equipped with a 40mm imaging probe. The pump and tubing are those used in the monophasic flow experiments, with a lower flow rate (50 L/min) as the section is smaller. Air is mixed with water using a mass flowmeter and a cylindrical injector. Air / water fraction where between 0 and 20%.



Experimental setup in the 600 MHz spectrometer



1D profile while a bubble is crossing

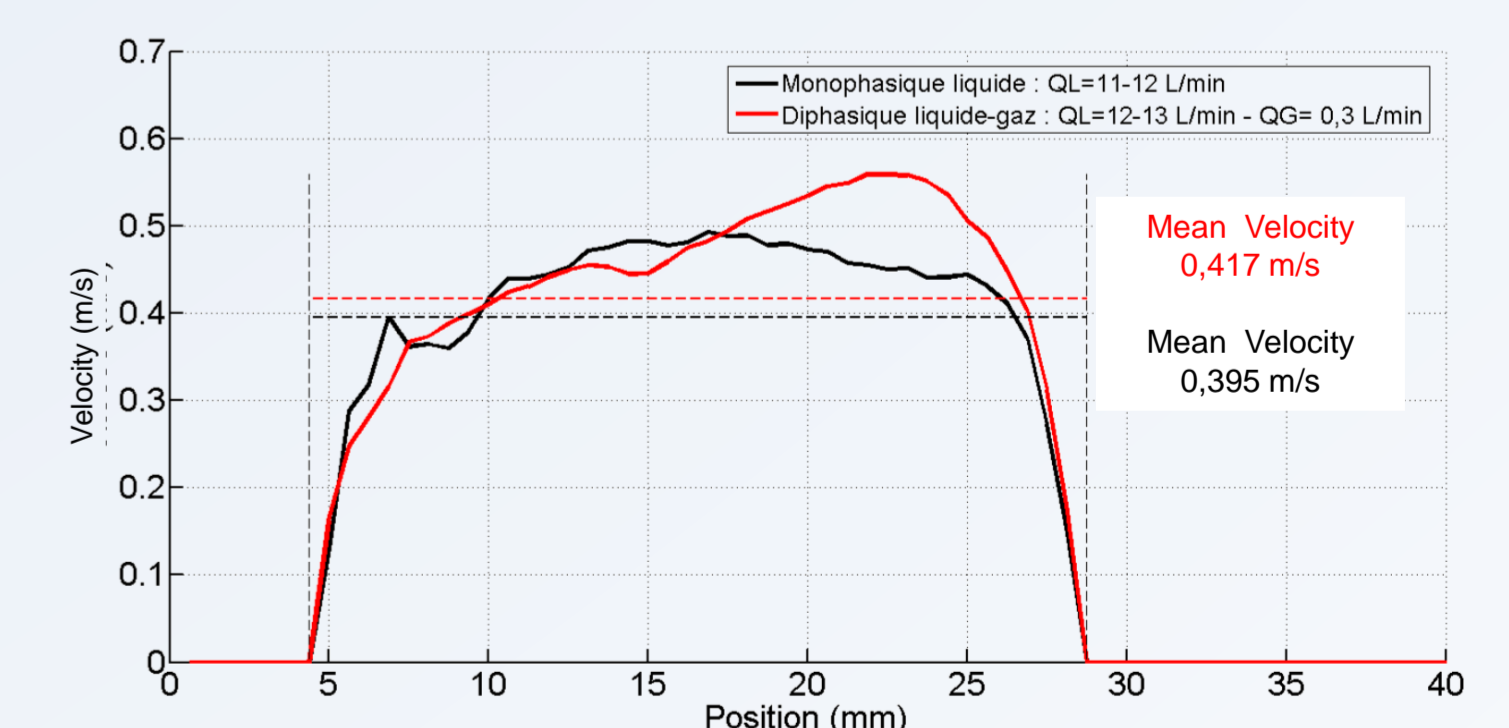


1D profiles stacked horizontally

Experiments with flow

The measure of the air water fraction can still be achieved when there is a flow. We have to take in account the modification of the water flow rate inside the measuring cell when the air/water ratio is high (the water is accelerated in this case, leading to a lower transit time in the probe and therefore a lower signal).

Imaging experiments with a high flow rate and bubbles leads to two difficulties with contradictory solutions : the susceptibility effects caused by the multiples air/water interfaces can be mitigated by using spin echo experiments but the experiments are not compatible with flow rate over 1m/s (even with very low echo time).



Comparison of the 1D velocity profile with air flow (red) and without (black)

Experiments without flow

Two experiments were carried out without water flows :

- Measure of the air water fraction as a function of the air flow rate. These experiments are simple one pulse experiments detecting the signal in the volume of the probe. There is a good agreement between the measured fraction and the theoretical one.
- Observation of bubbles ascension inside the tube. One dimensional spin echo experiments were performed, with an acquisition time of 25ms. A velocity of 25m/s can be calculated from the evolution of the position of a bubble as a function of the time

Conclusion

MRI has proved to be an invaluable tool to measure velocities in complex geometries. Difficulties arise with high velocities or in the presence of bubbles, but these difficulties can be overcome with carefully selected parameters and experiments. 1D profiles have shown to be interesting as the absence of phase gradient allows us to obtain images even in difficult conditions and very quickly. It is also possible to repeat a lot of these experiments (2 or 3 thousand time) in order to obtain statically significant results.

Other experiments will be tested such as CPMG with flow, as they have shown to give fast and precise velocities.

References

Velocity field and flow redistribution in a ballooned 7*7 fuel bundle measured by magnetic resonance velocimetry. A.V.S. Oliveira, D. Stemmelen, S. Leclerc, T. Glantz, A. Labergue, G. Repetto, M. Gradeck, Nuclear Engineering and Design, 369, 110828 (2020).
Parametric effects on the flow redistribution in ballooned bundles evaluated by magnetic resonance velocimetry. A.V.S. Oliveira, D. Stemmelen, S. Leclerc, T. Glantz, A. Labergue, G. Repetto, M. Gradeck, Experimental Thermal and Fluid Science, 125, 110383 (2021).
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