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Simultaneous measure of temperature and velocity in fluids using MRI



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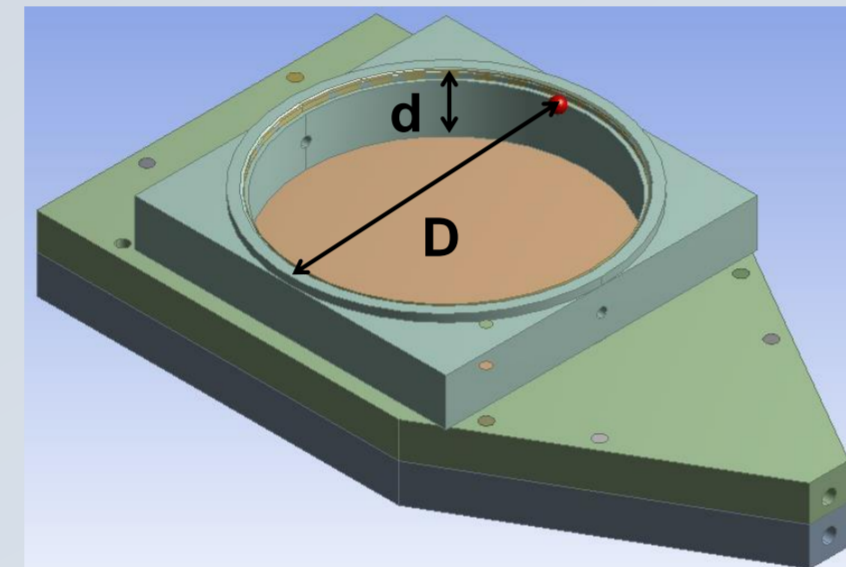
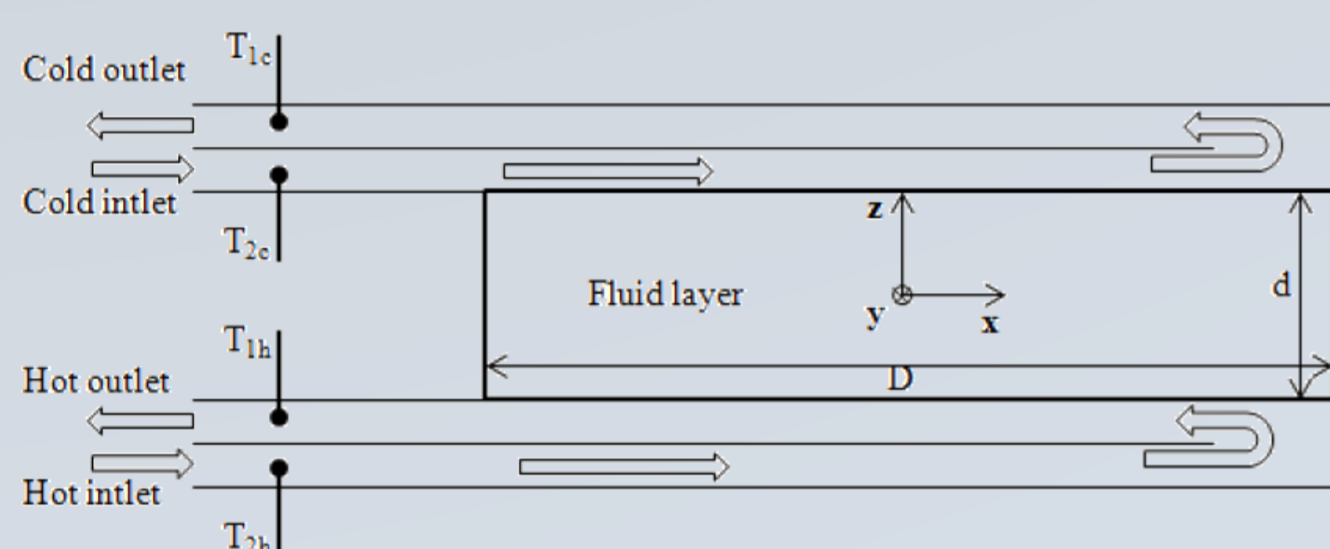
Objectives

The Rayleigh–Bénard convection (RBC) is a buoyancy driven instability in a fluid layer confined between two horizontal walls. The RBC in Newtonian fluids has been extensively studied since more than a century. These last decades, a growing interest has emerged for non-Newtonian fluids, mainly due to the wide fields of applications (e.g. oil, cosmetic, pharmaceuticals, food industries). As it is possible to measure with the same technique various physical quantities such as temperature or velocities, MRI is an interesting tool to study the RBC. Nevertheless, if velocity measurements using MRI are common in engineering sciences, temperature measurements with this technique are seldom used outside the medical field. Our goal is to benchmark the various MRI thermometry techniques, choose the one most adapted to our problem and look at the potentialities and limits of this method.

Experimental setup

The fluid layer is confined in a cylindrical cell which is $D=120$ mm in diameter and $d=20$ mm thick providing an aspect ratio of 6. The aspect ratio value is limited by the MRI resonator. All materials used in the setup have been chosen non-metallic to do not disturb the MRI measurements. The lateral walls are made of polymethyl methacrylate (PMMA) of 3 mm thick which is an insulated thermoplastic material. The horizontal walls are made of sapphire, a very good thermal conductor. Temperatures at these walls are imposed by using circulating water obtained via refrigeration units.

The experiments were performed on a Bruker Biospec 24/40 (2,34T). The experimental setup was placed inside a 16 cm diameter volume resonator.



Velocity measurements

Velocity images are obtained using a classical spin-echo imaging sequence with additional bipolar gradient pulses in order to encode the velocity. Two images are acquired with different gradient amplitude (0 and 180 mT/m) and the difference of the two images gives the velocity image.

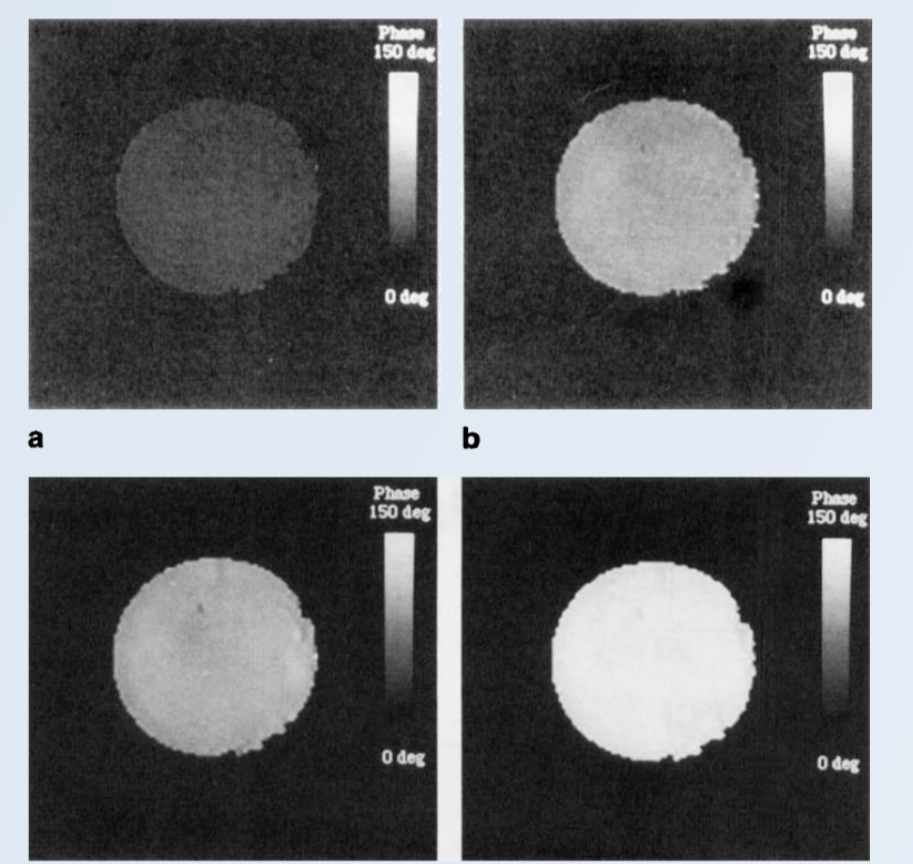
Spin echo sequence is used because it is immune to the chemical shift effect arising from the temperature difference. We have checked that dephasing caused by temperature does not occur due to the bipolar gradients. For this purpose, the dephasing has been measured in the case $\Delta T = -19.5^\circ\text{C}$ (conductive regime without any motion). In the range of our experimental parameters, we did not observe any significant dephasing caused by temperature variations in the velocity sequences.

Temperature measurements methods

Phase imaging

The chemical shift variation (frequency variation) due to temperature leads to a phase shift in the images. This technique is the most commonly used in the medical field.

- Fast acquisition
- Good precision for some fluids
- Need a reference image acquired without temperature shift, which is a problem in our setup (long time between each temperature steps).

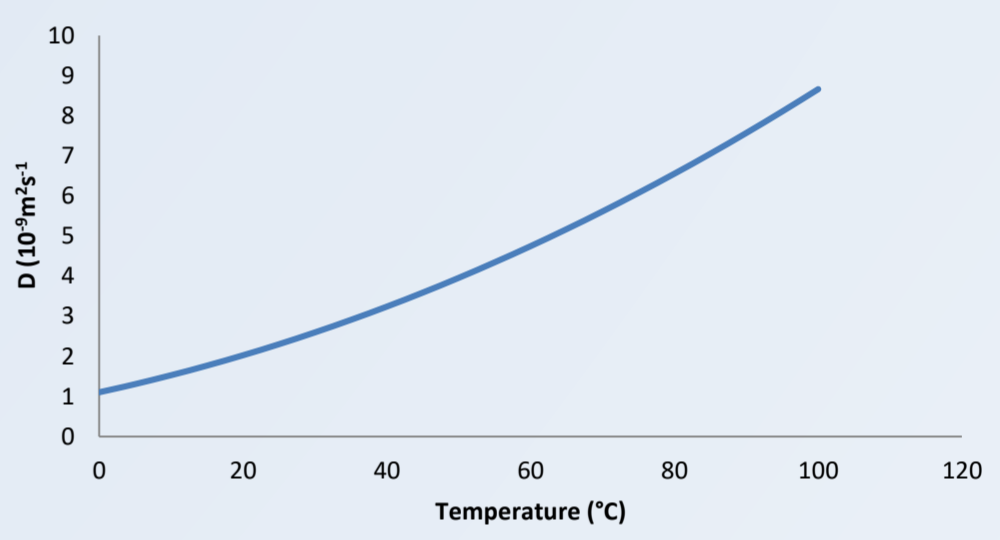


Phase maps for a 1% NaCl solution. The phase differences in images (a), (b), (c), (d) reflect temperature changes ΔT of 4°C, 8°C, 12°C and 16°C. Extracted from : Shapiro et al. Magnetic Resonance in Medicine, 47, 492-498 (2002)

Diffusion imaging

Due to the linear dependence of the self diffusion coefficient to temperature, diffusion imaging can be used for thermometry

- Main advantage : this technique does not need a reference image, Stokes-Einstein law gives the relation between Temperature and Diffusion.
- Problems with some viscous fluids, as the diffusion coefficient is low and hard to measure (e.g. glycerol)
- Modification of the diffusion coefficient with the velocity of the fluid (dispersion).



Self diffusion coefficients of water as a function of the temperature

Relaxation imaging

Relaxation in NMR is the process by which magnetization, after a perturbation goes back to its equilibrium state. To take into account this effect, two relaxation times are used: T1 for the longitudinal component of the magnetization and T2 for the transverse one.

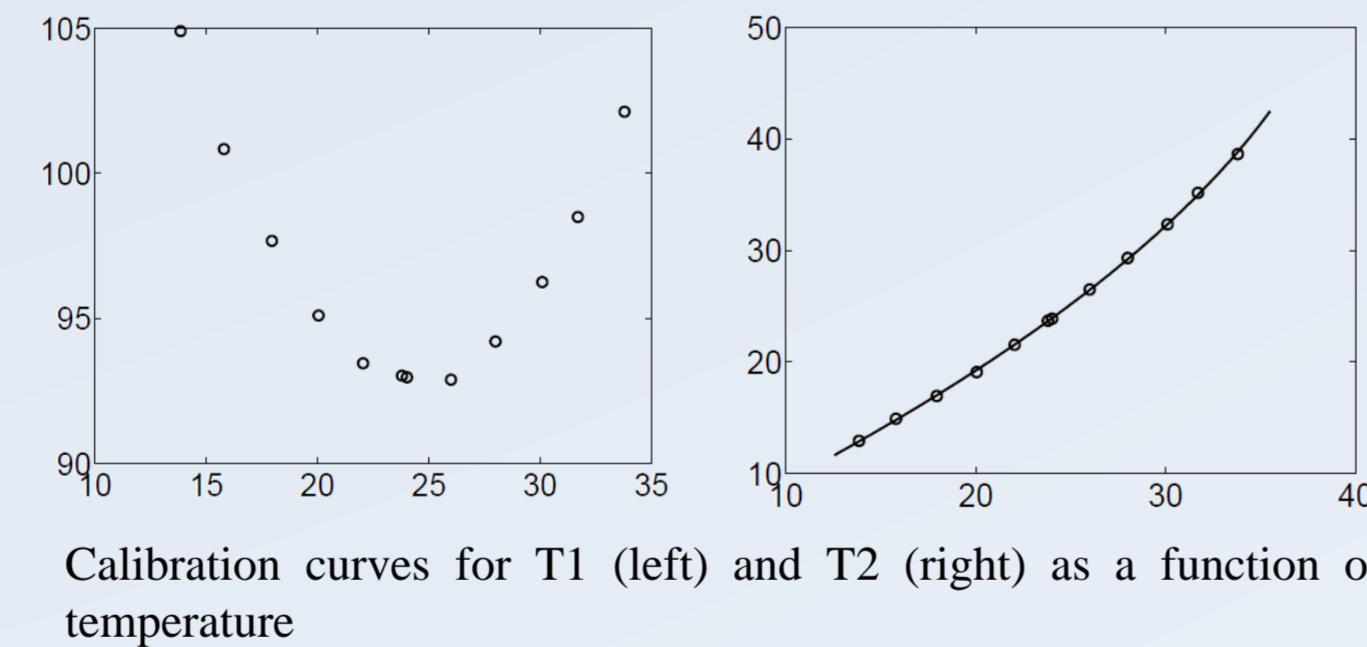
- Need to know the correlation between the relaxation times and the temperature for each fluid (calibration curve)
- Most “universal” technique, but with less accuracy

Results

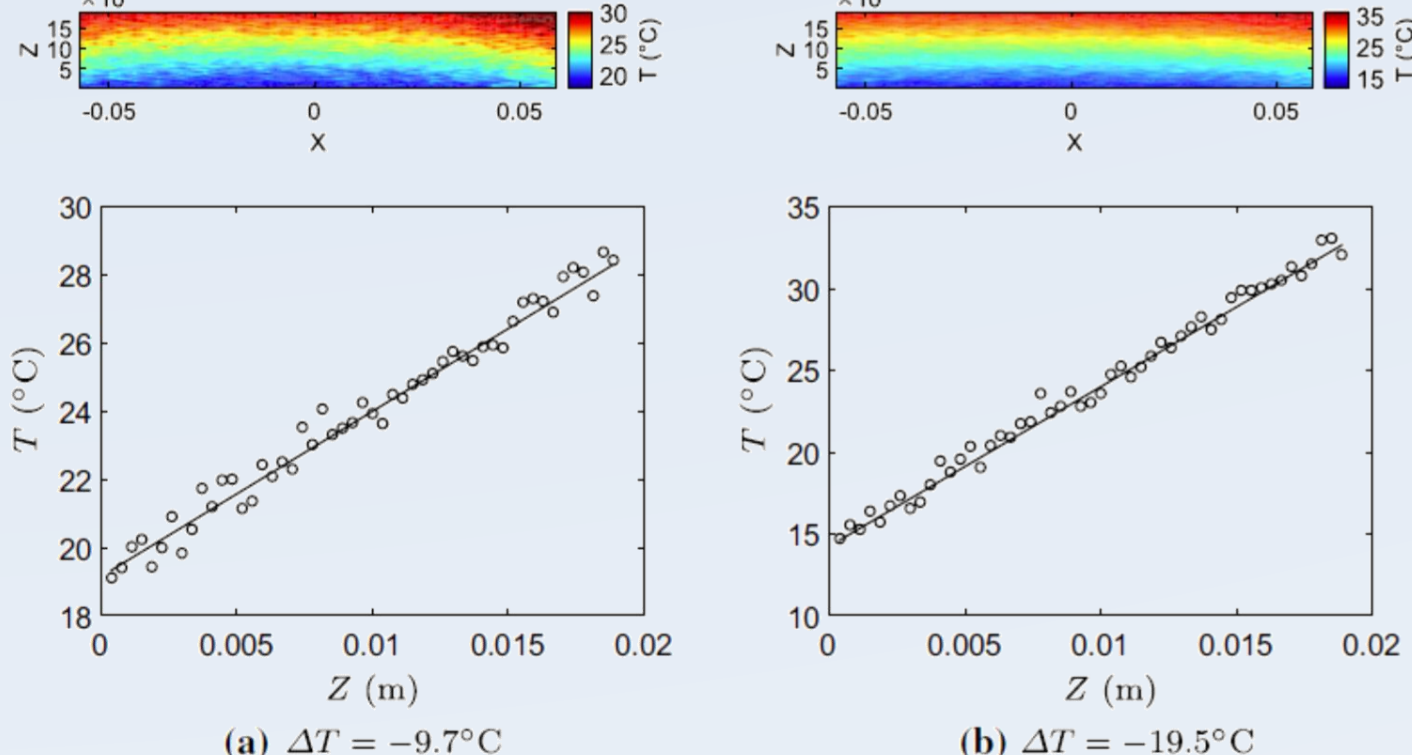
Relaxation imaging was the most relevant method in our case. Phase imaging needs a reference acquired before the start of convection, and as our magnetic field is not stable enough in such a timeframe, we can not use this method. Diffusion measurements can not be used due to the convective flow. We tried the technique on two systems : glycerol and xanthan.

Glycerol

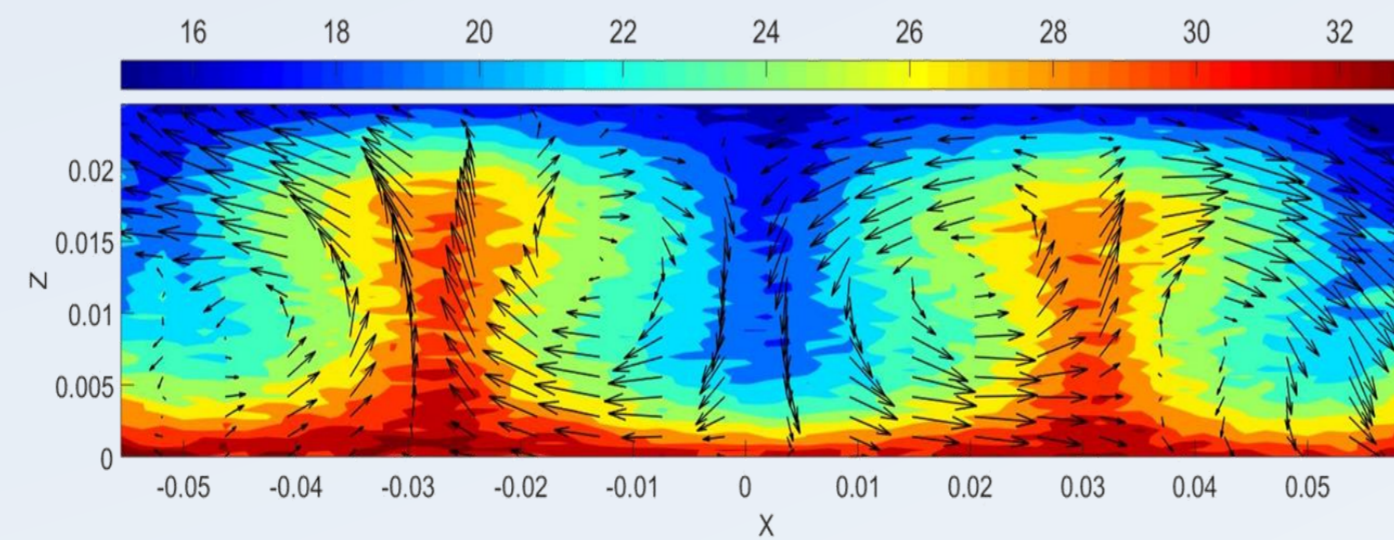
Concerning the longitudinal relaxation time T1, we observed that two values of temperature are possible for a given T1. As it is difficult to discriminate one temperature value, T2 imaging is preferable in the case of glycerol. We used multiple echo spin-echo experiments to acquire these images.



Calibration curves for T1 (left) and T2 (right) as a function of temperature



Temperature field (upside) of a conductive regime in the horizontal plane and temperature profile at the center (downside) along the vertical coordinate Z. Continuous lines: theoretical conductive temperature profile

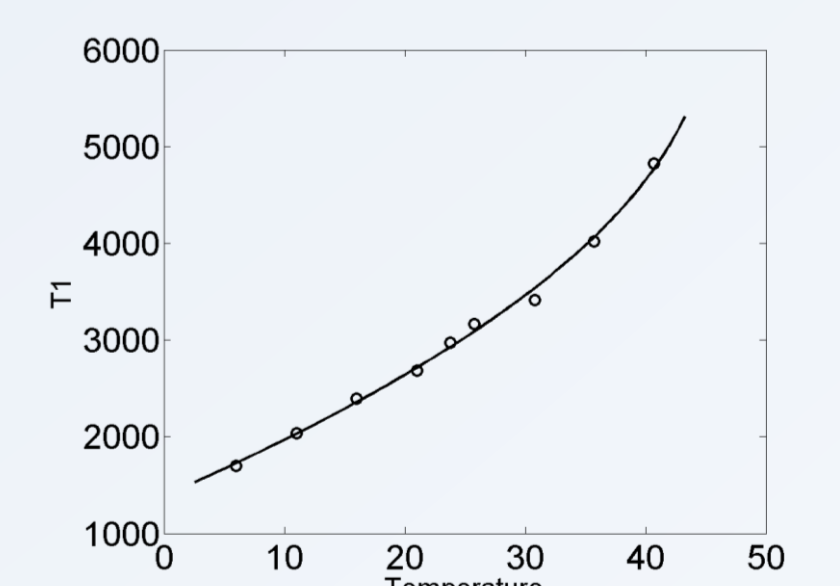


Superimposition of the velocity vectors on the temperature field for $\Delta T = 13.7^\circ\text{C}$, $Ra = 7795$

Xanthan

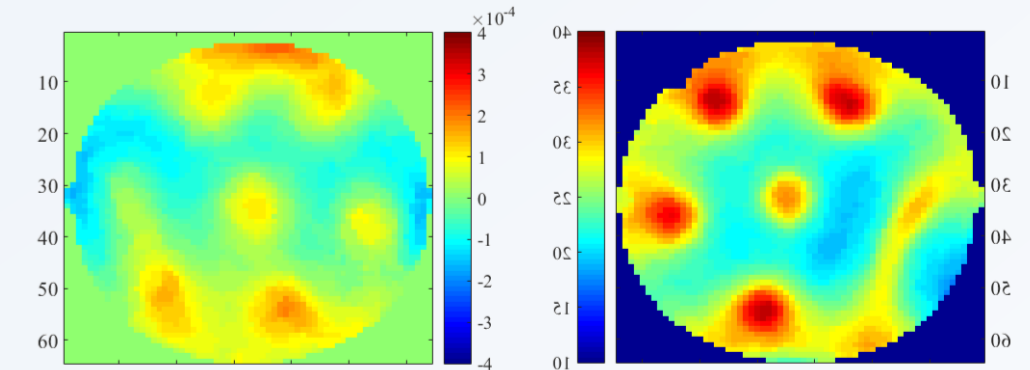
Xanthan is a shear thinning fluid. We used a 0,15% solution of xanthan in water, with a viscosity (Newtonian plateau) close to the glycerol. The relaxation times T1 and T2 of this solution are two order of magnitude greater than those of glycerol. Due to these high values, the T2 maps were not accurate (the variations are due to the effect of diffusion during the echo time).

On the contrary, as T1 shows a good variation with temperature, we were able to acquire good thermometry maps using spin echo experiment with variable repetition time.



Calibration curves for T1 in a 0,15% xanthan solution as a function of temperature

We obtained a good agreement between temperature and velocity maps for small temperature differences, up to 20°C. As this difference increased, we observed in the horizontal images erroneous results at the position where velocities were maximum. This effect was probably caused by water molecules entering the selected slice during the acquisition time. We used an experimental procedure to saturate the magnetization of the water molecules above and under the considered slice. After using this technique, the temperature images were again in agreement with the velocity ones.

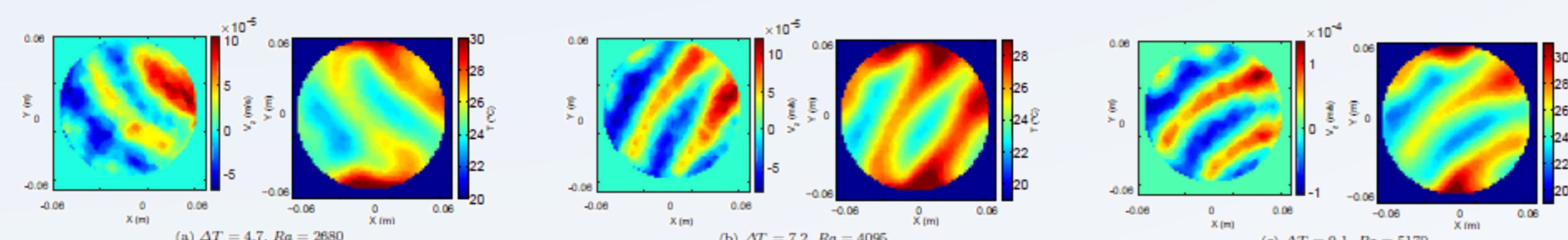


Comparison between velocity (left) and temperature (right) imaging $\Delta T = 18^\circ\text{C}$ in xanthan. The images were acquired in a horizontal plane in the middle of the cavity

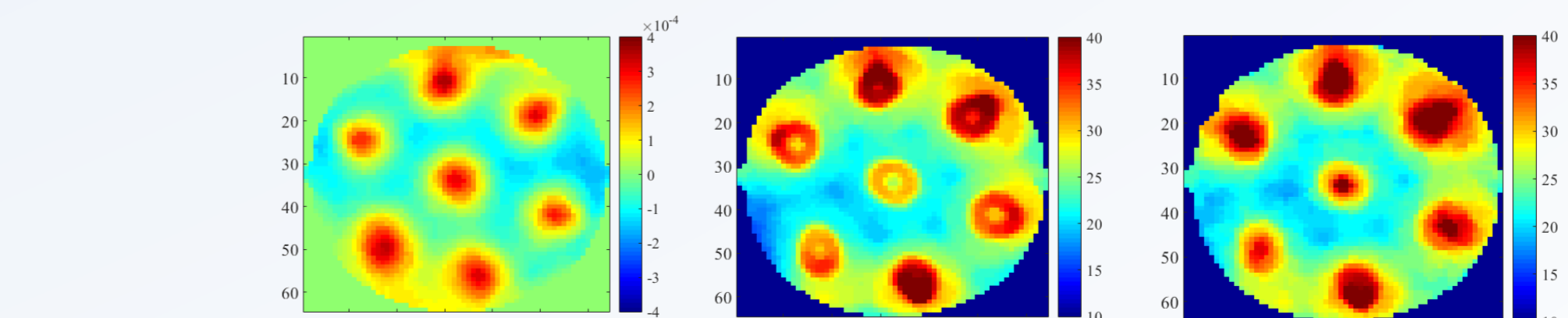
We acquired temperature images in two thermal regimes. In the conductive regime, temperature at the higher wall is superior to the one at the lower wall. In the convective regime, we used the inverse configuration.

Conductive regime allowed us to verify the agreement between the temperature measurements and the theoretical profile.

In the convective regime, when comparing the temperature and velocity fields obtained by MRI, we get an excellent agreement in terms of flow structure. Temperature uncertainties are found to be less than 1°C for all our results.



Comparison between velocity (left) and temperature (right) imaging for various temperature differences in glycerol. The images were acquired in a horizontal plane in the middle of the cavity



Comparison between velocity (left) and temperature images obtained without outside saturation (center) and with this procedure (right). The images were obtained for $\Delta T = 36^\circ\text{C}$ in xanthan.

Reference :

MRI temperature and velocity measurements in a fluid layer with heat transfer. S. Leclerc, C. Métivier, Experiments in Fluids (2018) 59, 34