# How MRI can assist Rheology?

Maude Ferrari, M. Jenny, Sébastien Kiesgen de Richter, Sebastien Leclerc, Christel Metivier, Zhidong Zhang, Philippe Coussot

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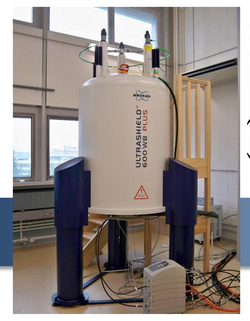
## Introduction

Rheology is the study of the flow of matter in response to an applied force. The studied fluids are often complex and the standard macroscopic rheology analysis is not sufficient to understand certain phenomena associated with flow or material heterogeneities. A **local** rheology analysis is then crucial. In addition, the **MRI technique** is a convenient solution especially when the fluid is opaque. Here are three examples of application.

Bruker Avance III WB



600MHz(¹H)

14,1T
ø max = 4cm
Gradient 150G/cm
Rheo-NMR system

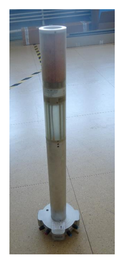
Bruker Biospec 24/40

100MHz(¹H)

2,35T
ø int = 16cm
Gradient 20G/cm

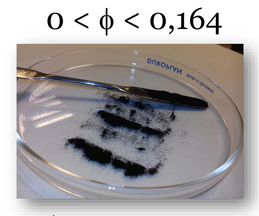
## Thixotropic suspension

The study of **non-Brownian fiber suspension** rheometry in a Taylor-Couette device is done thanks to the velocity profiles obtained by MRI measurements (flow encoding spin-echo protocol). The local rheological data are acquired for different shear rates and volumetric factions.

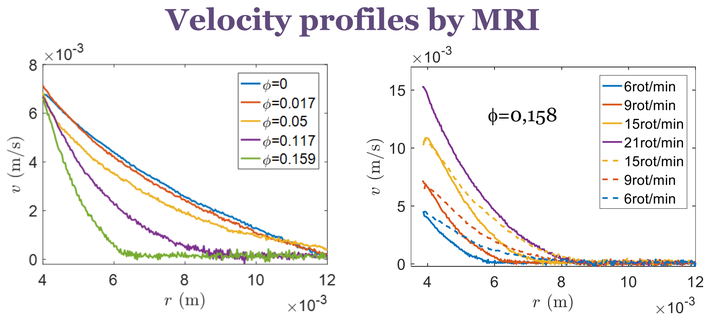


micro-imaging probe (MicWB57) Bruker

Non-Brownian fibers
$l$=500µm ø 18µm
0 < ϕ < 0,164

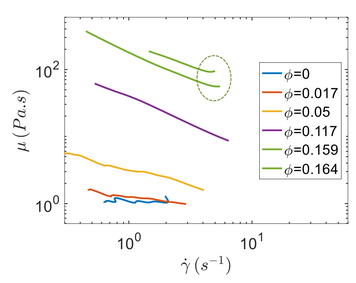


### Velocity profiles by MRI

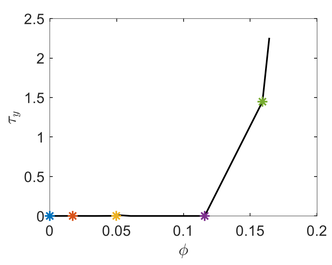



Highlighting of the irreversible behavior and presence of a threshold (localized flow)

### Local rheology obtained from MRI for different volume fractions $\phi$ at Ω = 9 rpm.

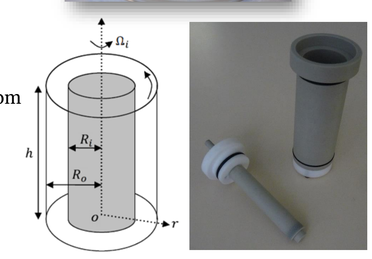



### Critical value of volume fraction




The orientation and/or migration of the fibres are therefore very important parameters influencing the rheology of these suspensions.

Ω= 6 à 60 rpm
$r_i$= 14mm
$r_o$= 31mm
$h$= 84mm




Taylor Couette device

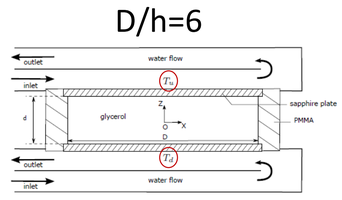
| ϕ= 0 (solvant) | Newtonien | ϕ= 0,017 | Shear Thinning | ϕ= 0,05 Caractère irréversible | ϕ= 0,117 | Yield stress | ϕ= 0,159 γ élevé | Shear Thickening |
|---|---|---|---|---|---|---|---|---|
| Little interaction between fibers<br>Constant viscosity + Speed profile: all the fluid is flowing | | | Fiber organization and orientation<br>Irreversible character + Viscosity decreases | | Frozen zone in velocity profile | | Jamming<br>Critical volume fraction | |

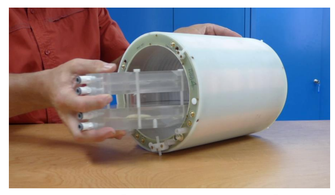
## Temperature et velocity measurements

The study of thermal transfer by **conduction** and **convection** represents a wide field of industrial and environmental applications. We investigate the possibility to measure **velocity** and **temperature** profiles with MRI in a fluid layer submitted to heat transfer.

- Velocity measurements : spin-echo imaging sequence + gradient dipolar
- Temperature measurements : T2 calibration

D/h=6

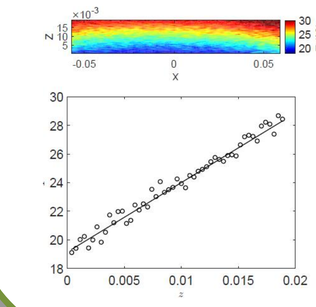


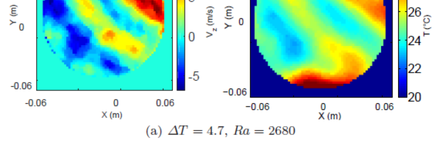
160 mm diameter quadrature resonator (Doty)

### Glycerol ( Newtonien fluid)

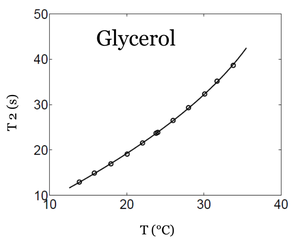
Conduction (Td<Tu)
Vertical stratification

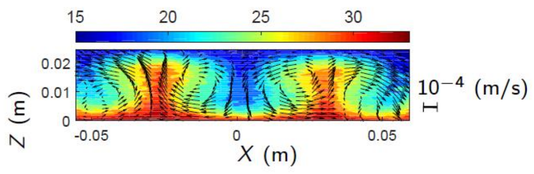



Convection (Td>Tu)
Rolls



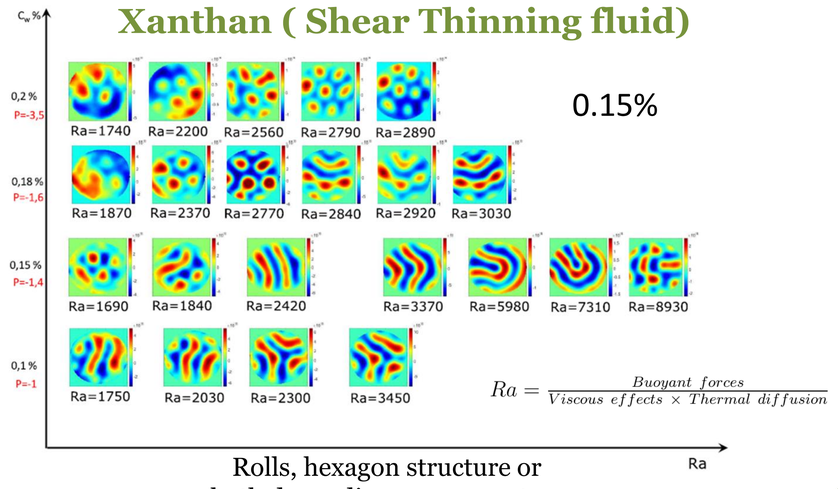

(a) $\Delta T = 4.7$, $Ra = 2680$




Temperature resolution : 1°C
Spacial resolution : 400µm

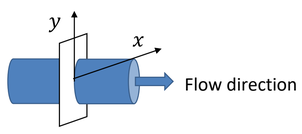
### Xanthan ( Shear Thinning fluid)




Rolls, hexagon structure or both depending on parameters

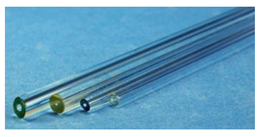
## Wall slip mechanism

We carried out a series of experiments with the aim of completing our knowledge of wall slip characteristics. The study is based on internal measurements of the velocity profile of inverse emulsion into a capillary tube. They are acquired using a flow encoding spin-echo protocol with in addition bipolar gradient pulses in order to encode the phase shift arising from the flow.




- linear variation of the velocity with the stress
- At the approach of the yield stress value the velocity increases steeper ≈ quadratic law

⇒ A change of both regime and physical process for wall slip when the yield stress fluid is in its liquid regime along the wall



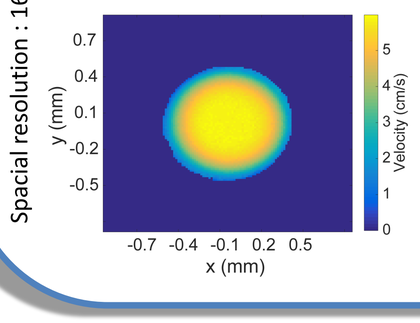
glass capillaries of different diameters (0.6 to 2 mm).

Micro-imaging probe (MicWB40) Bruker

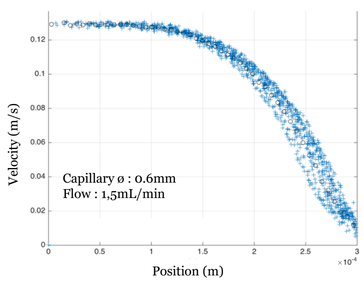
flow rate-controlled syringe

### Inverse emulsion 73%

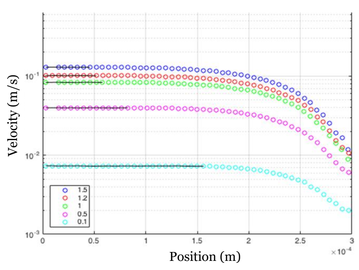
Spacial resolution : 16µm



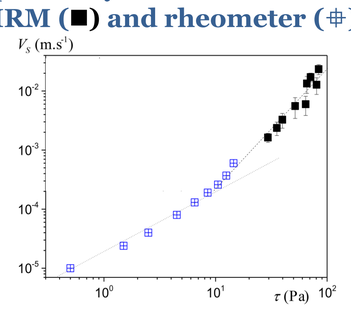

### Velocity profile




### Average velocity profile at different flows




### Slip velocity *vs* shear stress from IRM (■) and rheometer (⌗)

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Jenny, Ferrari, Gaudel, Kiesgen de Richter, EPL (2018)

Leclerc, Métivier, Exp. Fluids (2018)

Zhang, *et al.*, J. Rheo. (2018)