Microimaging

RheoNMR

Laboratory on a Chip

Dieter Gross MRS / User Meetings 2016
RheoNMR
Combination of Rheology
MR Microscopy
MR Spectroscopy

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RheoNMR

Rheology deals with deformation and flow of matter

Figure 2: Schematic drawing of surfactant aggregates (micelle, lamellar structure and inverse micelle) forming in water with increasing surfactant concentration and temperature from left to the right.

Figure 86: Schematic drawing of possible way of vesicle formation from $L_n$ phase induced by a temperature jump.

Rheology is everywhere in our daily life
Evaluation of more RheoNMR Applications

Applications were shown in

- medicine, pharma, health care, viscosity dependence versus concentration of monoclonal antibodies in medicine,
- food, water, correlation of mouth feel and strain measurements of new food, psycho-rheology, food sensor perception, triborheology combination of tribology and rheology,
- climate, fuel, oil, alternative energies,
- microfluidics, micro-rheology, shear banding in complex fluids,
- strain hardening, polymer crystallization under shear,
- polyurethane synthesis, mixing & stirring,
- micro-rheology and serpentine rheometers,
- interfacial surface properties, surface tension versus bulk pressure,
Parameters

σ  Stress = Force/Area
ν  Velocity

\( \dot{\gamma} \) time dependent strain or strain rate

η  Viscosity = stress / strain

G viscoelastic modulus

G = stress / strain rate

\( G(\omega) = G'(\omega) + i \cdot G''(\omega) \)

G’ storage modulus (elastic)

G” loss modulus (viscous)
**RheoNMR**

Ares-2 Rheometer from TA Instruments

![Diagram of Ares-2 Rheometer](image)

Independent measurements of stress and strain

- **Couette cell**
- **cone&plate cell**
- **plate&plate cell**
- **tube**

**Modulus** = \( \frac{\text{Stress}}{\text{Strain}} \)

**Stress** = Viscosity

**Stress** = \( \frac{\text{Strain Rate}}{\text{Strain Rate}} \)

Bruker BioSpin
RheoNMR is the combination of

- Rheology
- MR Microscopy
- NMR spectroscopy
- Time Domain NMR (Relaxometry)

**Rheology** provides information about **mechanical properties** by viscosity, energy storage and energy loss modulus determination.

**MR Microscopy** provides information at the **mechanical length scale** by spatially and temporally resolved velocity maps and shear rate maps.

**NMR spectroscopy** provides information at the **molecular length scale** by spatially and temporally resolved NMR spectra, relaxation times and diffusion constants.
RheoNMR Accessory for MicWB40 Microimaging Probes

Components of the RheoNMR Accessory

Developed by Tim Brox and Petrik Galvosas, Victoria University of Wellington, NZ
Application Examples

Food
Micells
Polymers
Granular Flow
2H spectroscopy under shear
Cylindrical Couette Cell

sauce slips at the inner surface,
variable shear across the annulus,
low slip at the outer surface,
transition in shear rate,
shear thinning towards the outer surface

Courtesy of Paul T. Callaghan
Test the macroscopic properties:

“FLOW and PLOP”

The velocity is first decreasing, then increasing with radius, similar to plug flow.

Indication for yield stress properties.

Courtesy of Paul T. Callaghan
NMR Flow Visualisation of heterogeneous shear and extension:

The fundamental assumption of shear rate constancy is not valid for certain classes of fluid!

„Shear Banding“

Courtesy of Paul T. Callaghan
Shear Banding

Fluid separates into coexisting phases of widely differing viscosity.

Flow instability. Molecular ordering effects.

Courtesy of Paul T. Callaghan
Influence of Fluid Dynamics on Polymerization Kinetics Measured by Rheo-NMR

Construction of an appropriate Rheo-NMR equipment

E. Laryea, G. Guthausen, T. Oerther, M. Kind

Reaction Monitoring under Shear
The influence of fluid-dynamics on the kinetics of polymerisation observed by RheoNMR

Chemical reaction & NMR spectrum under shear

Reaction Monitoring under Shear

Courtesy of Nils Schuhardt and Esther Laryea, KIT Karlsruhe Germany
Free Radical Polymerization (FRP)

Decomposition

Initiation

Propagation

Termination

Solvent: Xylene

Theoretical decay of monomer; batch polymerization

\[ [M] = [M_0] \cdot \exp \left( \frac{2k_1 \cdot \sqrt{[I_0]}}{k_d} \cdot (\exp \left( -\frac{k_d \cdot t}{2} \right) - 1) \right) \]

with

\[ k_1 = \frac{k_p \cdot \sqrt{2 \cdot f \cdot k_d}}{\sqrt{k_t}} \]

R = Radical, I = Initiator, M = Monomer, P = Polymer, k \rightarrow Coefficients, f = Radical efficiency
Polymerization – Model System

Methyl methacrylate (MMA)

Poly (methyl methacrylate) (PMMA)

\[ \text{Chemical shift } \delta / \text{ppm} \]

\[ 8.0 \quad 6.4 \quad 4.8 \quad 3.2 \quad 1.6 \quad 0.0 \]

**Determination of monomer conversion by \(^1\text{H} \) NMR spectroscopy**

\(^1\text{H} \) NMR spectra of 50 wt% MMA, 49.5 wt% Xylene and 0.5 wt% AIBN initial composition, 400MHz 5mm Tubes
Construction – Rheo-NMR Cell

- Inner and outer cylinder made out of PEEK
- Gap width 1 mm
- Radius ratio $\eta = \frac{R_i}{R_o} = 0.895$
- Concentric arrangement realized by bearings
- Temperature control via a hot nitrogen stream
- Inner cylinder coupled with speed controlled drive
Spectra under shear

- Broad peaks induced by the measuring cell
- Workaround → fit by pseudo-Voigt functions
- Nonlinear least-squares solver

Fit is in good agreement with the experimental data

Experimental data
Chemical shift \( \delta \) ppm

Experimtatal data
Fit 1 (Xylene, c)
Fit 2 (MMA, a)
Fit 3 (MMA, b)

Methyl methacrylate (MMA)

Apparent shear rate: \( \dot{\gamma} = \omega \frac{R_i}{s} = 124 \text{ 1/s} \)
Results – Monomer Conversion

**Area Ratio**

\[ A(t) = \frac{A_{MMA}(t)}{A_{Xylene}(t)} = 0.53 \cdot e^{-4.17 \cdot 10^{-4} \cdot t} \]

**Monomer conversion**

\[ X(t) = \frac{A(t = 0) - A(t)}{A(t = 0)} \]

**Monomer concentration**

\[
[M] = [M_0] \cdot \exp \left( \frac{2k_1 \cdot \sqrt{[I_0]}}{k_d} \cdot \left( \exp \left( -\frac{k_d \cdot t}{2} \right) - 1 \right) \right)
\]

with \( k_d = 1.53 \cdot 10^{-4} \text{s}^{-1} \)

\[ k_1 = 2.7 \cdot 10^{-3} \frac{l^{0.5} \cdot \text{mol}^{0.5}}{s} \]

**Determination of reaction rate constant \( k_1 \) by \(^1\text{H}\) NMR spectroscopy**
The influence of fluid-dynamics on the kinetics of polymerisation observed by RheoNMR

Flowprofile in TCR

(a) Über FLOWMAP gemessene Geschwindigkeiten in $y$-Richtung von Wasser bei $\dot{\gamma} = 53 \, \text{s}^{-1}$. An der rot gestrichelten Linie sind die Geschwindigkeiten an dieser Stelle in (b) aufgetragen. Die berechnete Geschwindigkeit nach Gl. 2.41 mit $m_f = 1$ ist als durchgängige Linie aufgetragen. Der Wert der höchsten Geschwindigkeit ist für die Berechnung als Radius des Innenzylinders gesetzt worden.
Flow Observations of **Granular Material**

Granular material is defined as a collection of discrete macroscopic particles.

Natural examples include **sand, soil and snow**.

Numerous industrial processes involve granular material with examples from agriculture (e.g. **rice, sugar and seeds**) to pharmaceutical production.

Depending on the properties of the individual particles, overall volume concentration and applied external stimuli, granular materials can **behave as either a solid, liquid or gas**.

NMR is a **non-invasive** technique for studying materials under shear. The RheoNMR hardware is well suited for these studies.

The shear devices rheo cells can be **tailored to the diameters of particles** and the desired number of grains spanning the fluid domain in SB / WB and SWB magnets.

Courtesy of Tim Brox, Petrik Galvosas, Jenifer Brown, Joe Seymour, Sarah Codd, Hilary Fabich, Daniel Holland
### Table: Mean Diameter and Inter-Channel Distance

<table>
<thead>
<tr>
<th>Sample</th>
<th>Mean Diameter /mm</th>
<th>$r_i$ /mm</th>
<th>$r_o-r_i$ /mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lobelia Seeds</td>
<td>0.3</td>
<td>16.0</td>
<td>7.65</td>
</tr>
<tr>
<td>Petunia Seeds</td>
<td>0.5</td>
<td>16.0</td>
<td>7.65</td>
</tr>
<tr>
<td>Vitamin E Capsules</td>
<td>1</td>
<td>15.1</td>
<td>8.55</td>
</tr>
<tr>
<td>Mustard Seeds</td>
<td>2</td>
<td>11.1</td>
<td>12.55</td>
</tr>
</tbody>
</table>

Samples studies in a dedicated RheoNMR system for a super wide bore magnet.

Courtesy of Tim Brox, Petrik Galvosas, Jenifer Brown, Joe Seymour, Sarah Codd, Hilary Fabich, Daniel Holland
Pulse program for granular flow experiments: Double slice selection 1D imaging sequence with velocity encoding.

The broadband (hard) $\pi$ pulse in the PGSE portion allowed short observation times $\Delta$ over which fewer particle interactions would occur. The encoding time $\delta$ was fixed at 1 ms. For each system multiple experiments were conducted as a function of the observation time $\Delta$ varied between 1.8 ms to 7 ms.
Top: Axial MRI data for the four granular material systems; (left to right) lobelia seeds, petunia seeds, vitamin E capsules and mustard seeds. All images were 60mm by 60mm (256 points by 256 points).

Bottom: Velocity profiles for the respective granular system. In each experiment the motor was rotated such that the tangential wall speed was 17.1 mm/s; All velocity data were acquired with an encoding time $\Delta = 5$ ms.

The vertical dashed lines indicate the boundaries of the shear cell while the horizontal dashed line indicates the velocity of the moving wall.

Courtesy of Tim Brox, Petrik Galvosas, Jenifer Brown, Joe Seymour, Sarah Codd, Hilary Fabich, Daniel Holland
Spatially resolved velocity measurements could be used to describe the variance in particle velocities.

By observing the variance of velocity as a function of observation time $\Delta$ it would be possible to estimate the mean collision time;

At observation times less than the mean collision time the variance of velocity is constant.

These mean collision times relate to the rheology and viscosity of the granular material and would be of great use for refining theoretical descriptions of granular flow.

NOTE: This type experiment and interpretation of granular flow behavior at different $\Delta$ is somehow similar to restricted diffusion experiments using short and long diffusion times $\Delta$. 

Courtesy of Tim Brox, Petrik Galvosas, Jenifer Brown, Joe Seymour, Sarah Codd, Hilary Fabich, Daniel Holland


RheoNMR

$^2\text{H}$ as a “tracer” for local order in systems under shear

$^2\text{H}$ as a “tracer” for local order in flowing systems

The spin 1 deuteron quadrupole moment interacts (of D$_2$O or other deuterated solvents) with the electric field gradients caused by the surrounding molecules (micelles, wormlike surfactants) causing $^2\text{H}$ spectral splitting depending on the local order in systems.

This can be used to probe the type and degree of ordered systems under shear by $^2\text{H}$ spectroscopy.

$$H_Q = \frac{3eV_{zz}Q}{4I(2I-1)\hbar} \left( \frac{3\cos^2\theta_{ij} - 1}{2} \right) [3I_z^2 - I^2]$$

Courtesy of Tim Brox and Petrik Galvosas, Victoria University of Wellington NZ
Rheo NMR

Quadrupolar Interaction (Spin > 1/2)

\[
H_Q = \frac{3eV_{zz}Q}{4I(2I-1)\hbar} \frac{(3\cos^2 \theta_{ij} - 1)}{2} \left[3I_z^2 - I^2\right]
\]

\[\theta_{ij}\quad \text{Angle between the internuclear vector (e.g. C-D) and the magnetic field Bo}\]

\[Q\quad \text{Nuclear quadrupole moment}\]

\[V_{zz}\quad \text{Electric filed gradient tensor}\]

Orientation Dependence and Motional Averaging \(\theta_{ij}(t)\)
Quadrupolar interaction spectroscopy

shear induced order in the wormlike micelle solution of 18% CTAB / D$_2$O in 17 mm / 19 mm Couette cell

$^2$H spectra of D$_2$O as function of radial position across the gap of the Couette cell

Cetyltrimethylammonium bromide

Courtesy of Paul T. Callaghan
Formation of a nematic phase at high stress, transition through a mixed phase region, isotropic phase at low stress.

Outer wall: low stress, single line

Inner wall: high stress, line splitting, finite quadrupole interaction.
Observation of Shear Induced Structural Transitions in a Lyotropic Nonionic Surfactant System via deuterium spectroscopy

1. Mix triethylene glycol mono-n-decyl ether C$_{10}$E$_3$ in 9:1 D$_2$O:H$_2$O.

2. Load sample in Couette cell and shear it at 42$^\circ$ C and a shear rate of 10 s$^{-1}$ for approximately one hour to establish the planar lamella phase (as identified by $^2$H spectrum).

3. Once the L$_\alpha$ structure is established stop the motor and set the temperature to 25$^\circ$ C where the sample equilibrates for one and a half hours.

4. Acquiring data at a constant shear rate of 10 s$^{-1}$

5. NMR data was acquired. a total of 400 NMR experiments were run with a complete experiment taking approximately 14 s (total experiment time approximately 95 min)
Conclusions

- Spatially resolved velocity maps provide straight forward identification of **wall slip** and **information about granular flow**
- Spatially resolved velocity maps visualize changes in the shear behavior and identifies **shear bands**
- Spectroscopy under shear provides **reaction monitoring in situ** under shear conditions
- Deuterium spectroscopy under shear provides information about **local ordered or disordered structures on the molecular level**
- The combination of the NMR parameters with the traditional rheology parameters enables a better characterization and control of matter under flow and deformation
Acknowledgements !!!

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Lab on Chip for NMR Microscopy and Localized Spectroscopy

D. Gross, Bruker-Biospin GmbH Germany
Lab on a Chip

Standard equipment:

- Bruker Spectrometer
- Microimaging Accessory with 60 A gradient amplifiers
- Micro5 imaging probe and gradient (max strength: 4.8 G/cm/A = 2.8 T/m @ 60 A)
- ParaVision software
- Micro-coil rf-inserts
Lab on a Chip

**NMR Microscopy** with Isotropic Resolution below 10 μm Using Dedicated Hardware and Optimised Methods

- Multi-turn spiral surface coils
- Geometry suitable for flat samples (tissue slices, cell layers)
- Easy access
- Compatible with optical microscopy
- ID = 1000 – 20 μm, OD = 1300 – 158 μm

Samples in a Micro Chamber mounted on a Micro Coil

Micro Chamber  Encapsulating connector pieces  Micro Chamber assembled with the encapsulating connector

Courtesy of Vicent Estede, University of Valencia, Spain
Samples in a Micro Chamber mounted on a Micro Coil

Micro Chamber kit mounted on top of the Micro Coil Insert

Courtesy of Vicent Estede, University of Valencia, Spain
Micro Chamber mounted on a Micro Coil

Micro Chamber kit mounted on top of the Micro Coil Insert. Pure water was pumped through the support tubing.
Sample in a Micro Chamber mounted on a Micro Coil

overlay of the vector field and the FLASH image of water in the chamber (in black & white without flow) with the light microscope image of the chamber mounted on top of the microcoil
Lab on a Chip

Samples in a Micro Chamber mounted on a Micro Coil

Blocked flow regions !!!

MicroChamber fresh

MicroChamber Polluted !!!
Construction of a new surface coil design

Meadowcroft et al., 2007:

- Simple Design, Surface coil shape adapted to a meander sample cell or a Y-mixer

Courtesy of Dominik Meyer, Giesela Guthausen, Karlsruher Institut für Technologie (KIT), Germany
Flow in a Y Mixer

Courtesy of Dominik Meyer, Giesela Guthausen, Karlsruher Institut für Technologie (KIT), Germany
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T1 weighted image and Velocity Map H₂O-Ethanol

- Left: high signal intensity of water (shorter T1), low signal intensity of ethanol (saturation effect caused by longer T1)
- Right: higher velocity of ethanol,
- **Water is flowing partly into the ethanol input channel!**
- **No strong mixing!**

Courtesy of Dominik Meyer, Giesela Guthausen, Karlsruher Institut für Technologie (KIT), Germany
Human-on-a-chip concept

Thank you for your attention

RheoNMR

Laboratory on a Chip

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