Rheophysical investigation in concentrated particle suspensions

S. Wiederseiner, C. Ancey, N. Andreini & M. Rentschler

Laboratoire d’Hydraulique Environnementale
Ecole polytechnique fédérale de Lausanne

The Society of Rheology 80th Annual Meeting

August 3 - 8, 2008 - Monterey, California
1. Gravity driven geophysical flows
2. Rheology and Rheophysics
3. Concentrated particle suspensions
4. Measurement techniques and setup
5. Results
Geophysical flows

- Snow avalanches
- Mudflows
- Pyroclastic flows

Photo SLF
Geophysical flows

- Snow avalanches
- Mudflows
- Pyroclastic flows
Geophysical flows

- Snow avalanches
- Mudflows
- Pyroclastic flows
Geophysical flows
1. Gravity driven geophysical flows

2. **Rheology and Rheophysics**

3. Concentrated particle suspensions
   - Properties of the suspensions
   - Temperature effects
   - Wavelength effects

4. **Measurement techniques and setup**
   - FPIV / FPTV techniques
   - Measurement setup

5. **Results**
   - Validation
   - Velocity profile of concentrated suspensions
   - Flow curve derivation
Geophysical flows

Complex fluids
- Particles
  - Material
  - Shape
  - Granulometry
  - Rugosity
- Interstitial fluids
  - Viscosity

How do we measure the rheological properties?
- Yield stress
- Shear-thinning, Shear-thickening
- Thixotropy, rheopecty
Complex fluids

- Particles
  - Material
  - Shape
  - Granulometry
  - Rugosity
- Interstitial fluids
  - Viscosity

How do we measure the rheological properties?

- Yield stress
- Shear-thinning, Shear-thickening
- Thixotropy, rheopecty
Consequences for the rheologist

1. \[
\begin{bmatrix}
T \\
\Omega
\end{bmatrix} \rightarrow \begin{bmatrix}
\tau \\
\dot{\gamma}
\end{bmatrix}
\]

2. **Wide gap**
   (because of the granulometry)

Solve the Couette inverse problem

\[
\tau(r) = \frac{T}{2\pi r^2 h}
\]

\[
\Omega = \int_{R_{in}}^{R_{out}} \frac{\dot{\gamma}(r)}{r} dr
\]

- \(T\): Total Torque
- \(\Omega\): Angular velocity
- \(\tau\): shear stress
- \(\dot{\gamma}\): shear rate
- \(r\): Radius
- \(h\): Height of fluid
- \(R_{in/out}\): Radius of the inner/outer cylinder
Consequences for the rheologist

Example: an artificial Herschel-Bulkley fluid \( \tau = \tau_y + K\dot{\gamma}^n \)

\[
s = \frac{R_{in}}{R_{out}} = 0.9
\]
Consequences for the rheologist

The same fluid with a wide-gap geometry

\[ s = \frac{R_{in}}{R_{out}} = 0.2 \]
Example: a polymeric gel

Aney, J.Rheology 49 (2005) 441-460
Example: a particle suspensions


\( S \): adimensionalized shear stress
\( \Gamma \): adimensionalized angular velocity
Example: a particle suspensions


$S$: adimensionalized shear stress

$\Gamma$: adimensionalized angular velocity
Shear localization?
Particle segregation?
Particle migration?
Ordering?

Particle rugosity?
Particle Shape?
Slipping?

Do we measure the material property...

...or some flow artifacts?
Classical and optical rheometry

Continuum mechanics approach
  \[ \downarrow \]
  Classical rheometry
    \[ \downarrow \]
    \[ T \text{ and } \Omega \]
      \[ \downarrow \]
      Solve the Couette inverse problem
        \[ \downarrow \]
        \[ \tau \text{ and } \dot{\gamma} \]

Rheophysical approach
  \[ \downarrow \]
  Clear suspensions
    \[ \downarrow \]
    Particle motion (FPIV / FPTV)
      \[ \downarrow \]
      Differentiate the velocity profile
        \[ \downarrow \]
        \[ \tau \text{ and } \dot{\gamma} \]
Gravity driven geophysical flows

Rheology and Rheophysics

Concentrated particle suspensions
- Properties of the suspensions
- Temperature effects
- Wavelength effects

Measurement techniques and setup
- FPIV / FPTV techniques
- Measurement setup

Results
- Validation
- Velocity profile of concentrated suspensions
- Flow curve derivation
Properties of the suspensions

Where are the properties coming from?

Interesting flows

[Image of a flow]

concentrated particle suspensions (25mm thickness)

Optical methods

[Image of an optical method]
### Properties of the suspensions

#### The simplest complex fluid

- Iso-index ⇒ transparency
- Iso-density ⇒ No gravitation effects
- Molecular tagging of the particles ⇒ the laser excite the fluorescence

<table>
<thead>
<tr>
<th><strong>Particles</strong></th>
<th><strong>Fluid</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Shape : spherical</td>
<td>Three fluids mixture</td>
</tr>
<tr>
<td>Granulometry</td>
<td>Newtonian</td>
</tr>
<tr>
<td></td>
<td>Viscosity : variable</td>
</tr>
</tbody>
</table>
Temperature effects

Density

Refractive index
Temperature effects

Density

Refractive index

Dibromohexane: $-3.667e^{-04}$ \degree C
UCON oil: $-3.425e^{-04}$ \degree C
Triton X100: $-3.208e^{-04}$ \degree C

Linear fit

Adimensionnalized refractive index

Temperature [\degree C]

Dimensionless refractive index [-]
Temperature effects on the light transmission

 ![Graph showing temperature effects on light transmission](image)
Wavelength effects

Refractive index mismatch effects on the transmission

![Graph showing refractive index mismatch effects on transmission]
Wavelength effects
Wavelength effects

RGB picture with a color CCD camera:

Blue component

Red component
1. Gravity driven geophysical flows

2. Rheology and Rheophysics

3. Concentrated particle suspensions
   - Properties of the suspensions
   - Temperature effects
   - Wavelength effects

4. Measurement techniques and setup
   - FPIV / FPTV techniques
   - Measurement setup

5. Results
   - Validation
   - Velocity profile of concentrated suspensions
   - Flow curve derivation
Measurement methods
FPIV / FPTV techniques

Measurement methods

LASER SHEET
Measurement methods
FPIV / FPTV techniques

Measurement methods
Measurement setup

The setup
1 Gravity driven geophysical flows

2 Rheology and Rheophysics

3 Concentrated particle suspensions
   - Properties of the suspensions
   - Temperature effects
   - Wavelength effects

4 Measurement techniques and setup
   - FPIV / FPTV techniques
   - Measurement setup

5 Results
   - Validation
   - Velocity profile of concentrated suspensions
   - Flow curve derivation
FPIV Images
Validation measurements

\[ V_\theta(r) = \frac{A}{r} + Br \] with

\[ A = \frac{R_{in}^2 R_{out}^2 \Omega}{R_{out}^2 - R_{in}^2} \quad \text{and} \quad B = \frac{R_{in}^2 \Omega}{R_{in}^2 - R_{out}^2} \]
Velocity profile of concentrated suspensions

Time evolution of the suspension

Graph showing the velocity profile of concentrated suspensions over time. The graph compares the radial position (mm) against the radial velocity ratio $\frac{V_{\theta,r}}{V_{\theta,in}}$. The graph includes data points for after 1 hour, 2 hours, 3 hours, and 5 hours.
Velocity profile of concentrated suspensions

**Bottom end effects**

![Graph showing velocity profile](image)

- **Red stars**: 35mm from the bottom
- **Black stars**: 25mm from the bottom
- **Blue stars**: 10mm from the bottom

**Equation**: 
\[
\frac{V_{\theta,r}}{V_{\theta,in}} [-]
\]

**Axes**: 
- **R_in** to **R_out**
- Radial position [mm]

**Legend**: 
- 35mm from the bottom
- 25mm from the bottom
- 10mm from the bottom
Flow curve derivation

Flow curve comparison

\[ \dot{\gamma} [s^{-1}] \]

\[ \tau [Pa] \]

- velocity profile
- macsporran86
- tikhonov00
- ancy05
- dehoog06
- other methods
Futur work

We want to use the same techniques to make dam-break experiments and measure the inner velocity profile at the front.

See Poster 165 at the poster session.
Acknowledgment

- Christophe Ancey
- Nicolas Andreini, Martin Rentschler
- Michel Teuscher and his team
- The Swiss National Science Foundation
- Iso-index ⇒ transparency
- Iso-density ⇒ No gravitation effects
- not toxic

**Particules**
- Sphericity
- Good optical properties
- Granulometry
- Fluorescent molecular tagging

**Fluide**
- No evaporation
- Wet the PMMA
- Should not dissolve PMMA
- Low absorption
- No excitation
- Variable viscosity
Fluides

- Lyon (1997)
- Dibromohexane
- Triton X 100
- Huile UCON 75H
Transparent concentrated noncolloidal suspensions

- Spherical particles: 200 to 600 $\mu$m
- Iso-index and iso-density fluid mixture
Why Rhodamine 6G?
How much rhodamine 6G?

High concentration
⇓
More fluorescence
⇓
COMPROMIS
⇑
Lower effect on the refractive index
⇑
Low concentration
Produit brut

Produit brut PMMA BS 520

μ = 168.0 μm
σ = 54.33 μm
Produit tamisage par voie humide dans de l’?thanol
Choix de la Rhodamine 6G

- Excellent efficacité ?
- Suffisamment faible "Stokes shift"

Tuning curve Rhodamine 6G

- Pump wavelength: 532 nm
- Solvent: Ethanol
- Concentration: 0.09 g/l
- Range: 559 - 576 nm
- Max. eff. @ 568 nm
- Efficiency: 28%
Suspension properties

- Iso-index ⇒ transparency
- Iso-density ⇒ No gravitation effects
- Non toxic

**Particules**
- Sphericity
- Good optical properties
- Granulometry
- Fluorescent molecular tagging

**Fluide**
- No evaporation
- Wet the PMMA
- Should not dissolve PMMA
- Low absorption
- No excitation
- Variable viscosity