



# Flow of concentrated suspensions. Shear thickening

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# Outline

- Flow of non Brownian dispersions
- Rheology
- Measurement of the interactions.
- Velocity profiles
- Liquid fraction profiles.
- Outlooks and perspective

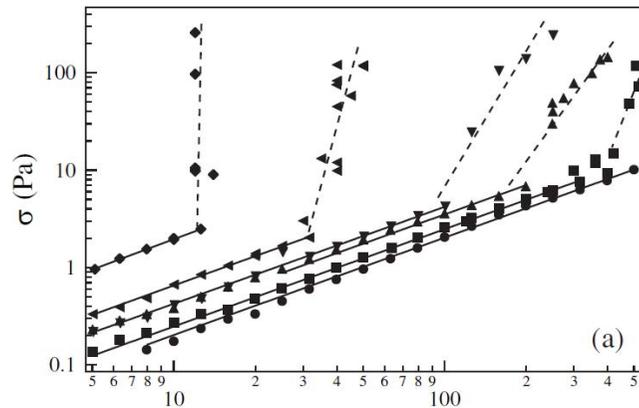
# Suspensions

- Paints, toothpaste, cement, sun screen cream



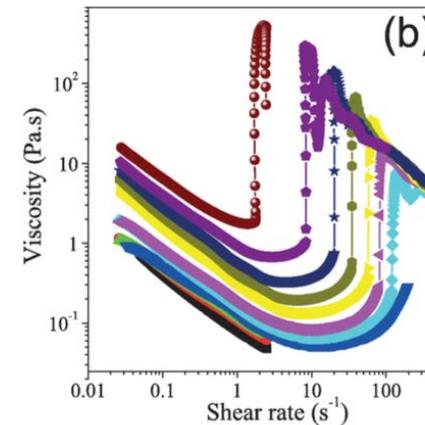
# Flow of particles

- Dense suspensions of solid particles immersed in newtonian solvent display complex flow properties.



*Lootens (2005)*

- Concrete, silica suspensions, cornflour mixtures, latex suspensions, clays are examples of shear thickening systems



*Ovarlez (PRL 2016)*

# Shear Thickening Consequences



Kevlar soaked with STFluids  
University of Delaware (Professor Wagner)  
in collaboration  
With US Army.



Continuous shear thickening leads to high costs when pumping concrete over long distances in large building sites. Credit: Concrete Forms/flickr.com

Shear thickening leads to high cost when pumping concrete over long distances in large building state.  
Shear thickening causes extrusion instabilities in the manufacture of plastic floors.

# Why does shear thickening occur?

The stress of non Brownian Suspensions is proportional to the shear rate.

*Pouliquen, Guazzelli*

Pi theorem a single dimensionless number:

$$Iv = \frac{\eta\dot{\gamma}}{P}$$

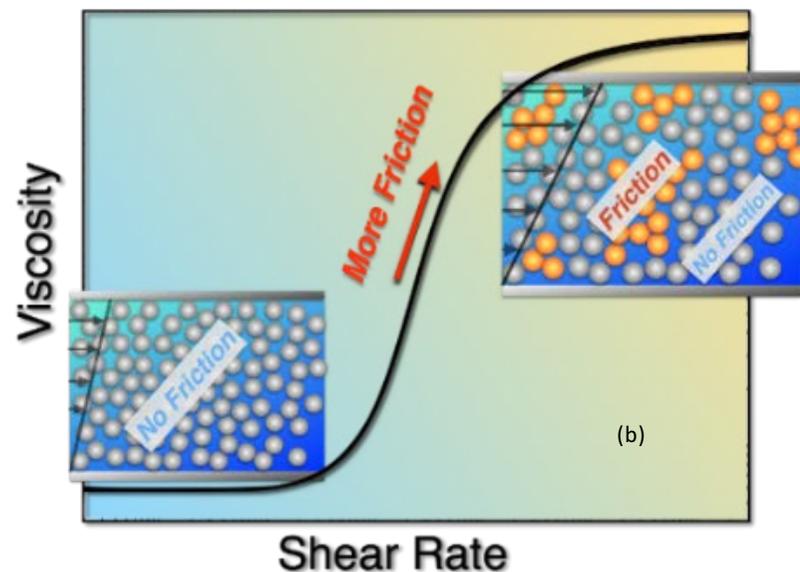
$$\tau = \mu(Iv)P$$

$$\phi = g(Iv)$$

$$\tau = \mu(g^{-1}(\phi)) \frac{\eta\dot{\gamma}d}{g^{-1}(\phi)}$$

$\mu(g^{-1}(\phi))$  varies as a function of the microscopic friction coefficient.

# Why does shear thickening occur?

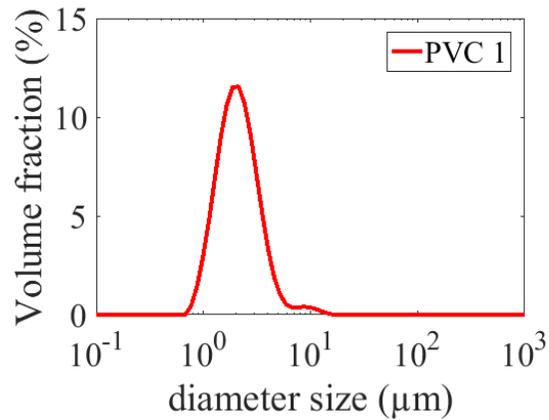
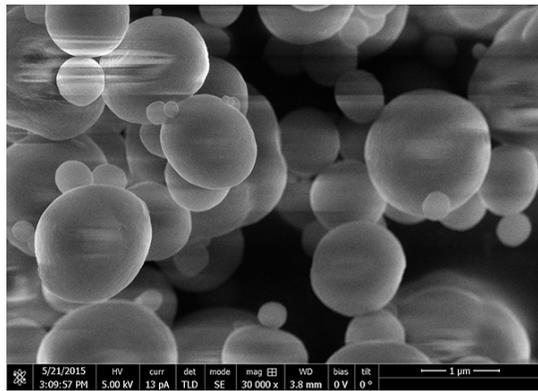


$\mu$  depends upon the applied stress

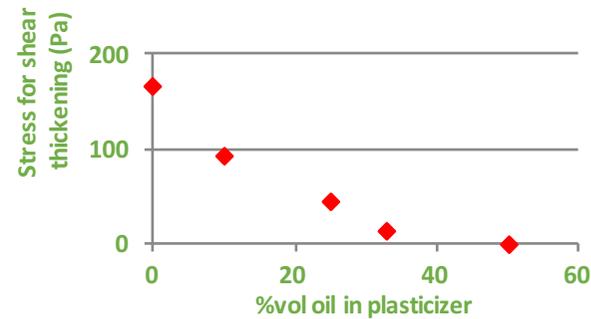
Shear thickening corresponds to a transition between a state with lubricated contacts between particles for low normal forces to a state with solid contacts between particles for high normal forces.

*J. Morris, R Seto, R Mari, JF Morris, MM Denn 2013 PRL Cates ,  
Wyart 2015 PRL, figure from Blair.*

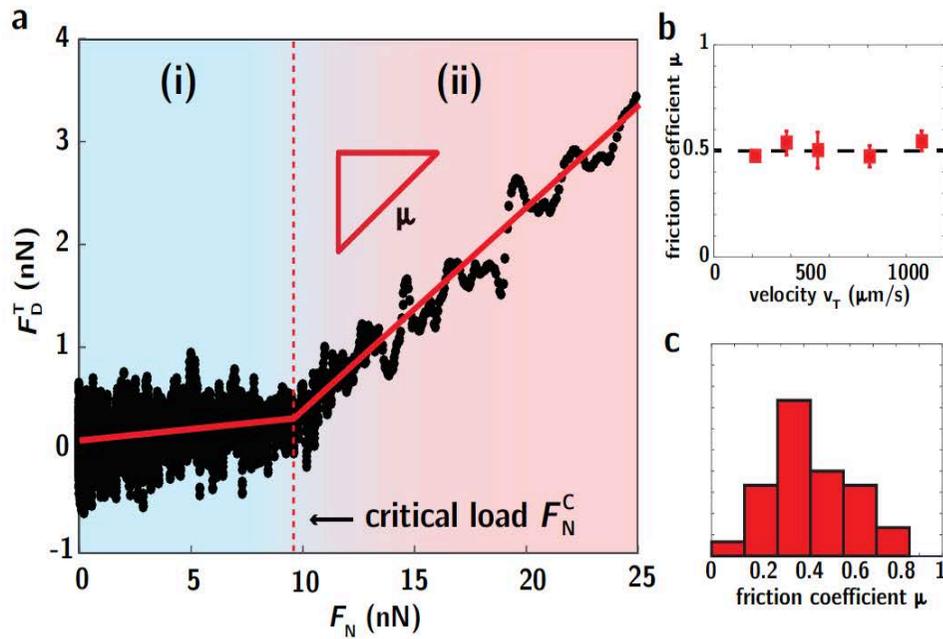
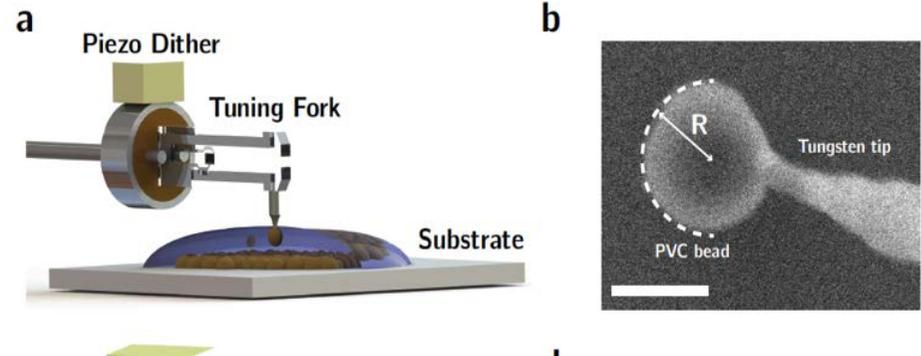
# PVC suspensions in plasticizer



Polyvinyl chloride (PVC) particles in 1,2-cyclohexane dicarboxylic acid diisononyl ester (Dinch). The continuous phase is Newtonian and has a viscosity of 41 mPa.s at room temperature. The density of PVC is 1.38 g/cm<sup>3</sup> and the density of Dinch is 0.95 g/cm<sup>3</sup>. The mean particle radius, defined as  $R_{32} = \langle R^3 \rangle / \langle R^2 \rangle$  is 1 μm. The size distribution is lognormal and the standard deviation estimated using the volume distribution is 45%.



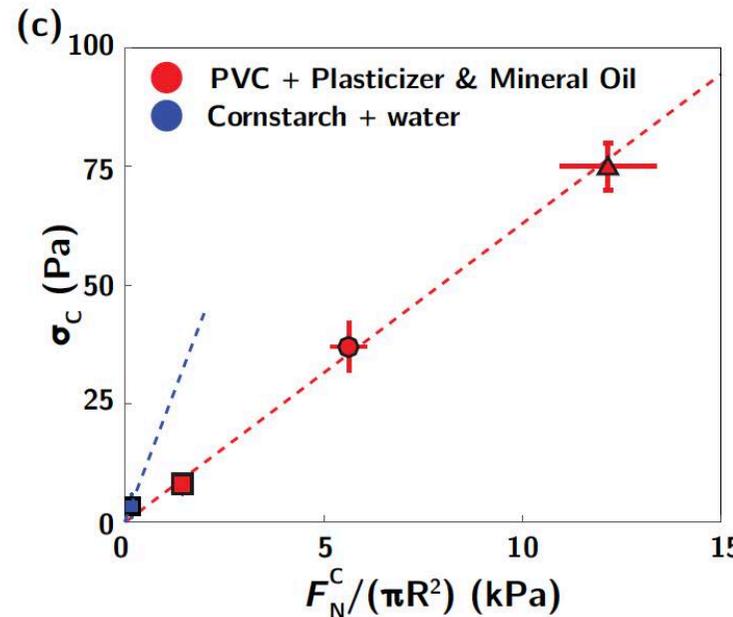
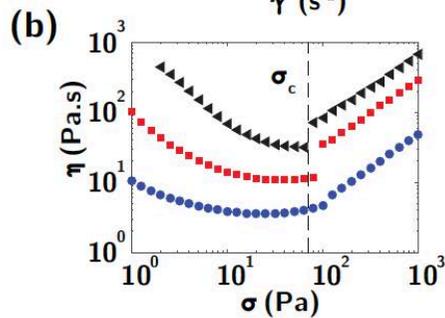
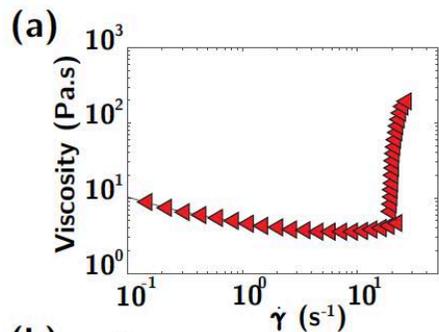
# Tuning Fork experiments



What is the critical load?

*Comtet et al Nature Com 2017*

# Bridging the gap between the micro and the macroscale



Shear thickening corresponds to a transition between a state with lubricated contacts between particles for low normal forces to a state with solid contacts between particles for high normal forces.

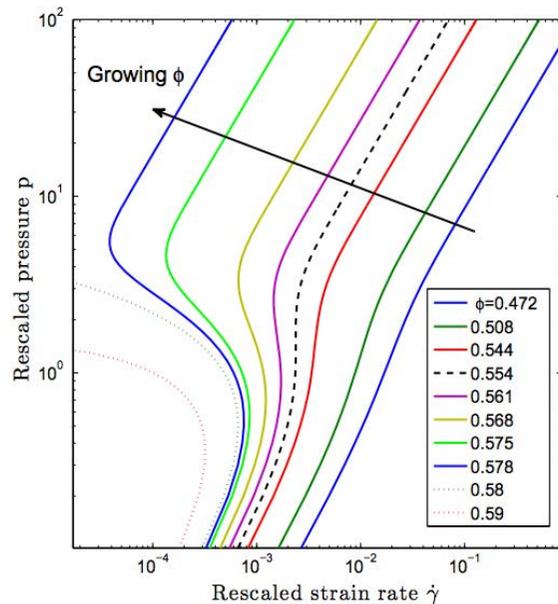
*Comtet et al Nature Com 2017*  
*Chatté et al Soft matter 2018*

Lin, N. Y., Guy, B. M., Hermes, M., Ness, C., Sun, J., Poon, W. C., & Cohen, I. (2015).

*Physical review letters*, 115(22), 228304. Clavaud, C., Bérut, A., Metzger, B., & Forterre, Y. (2017).

*Proceedings of the National Academy of Sciences*, 201703926.

# Feature of the flow during the transition

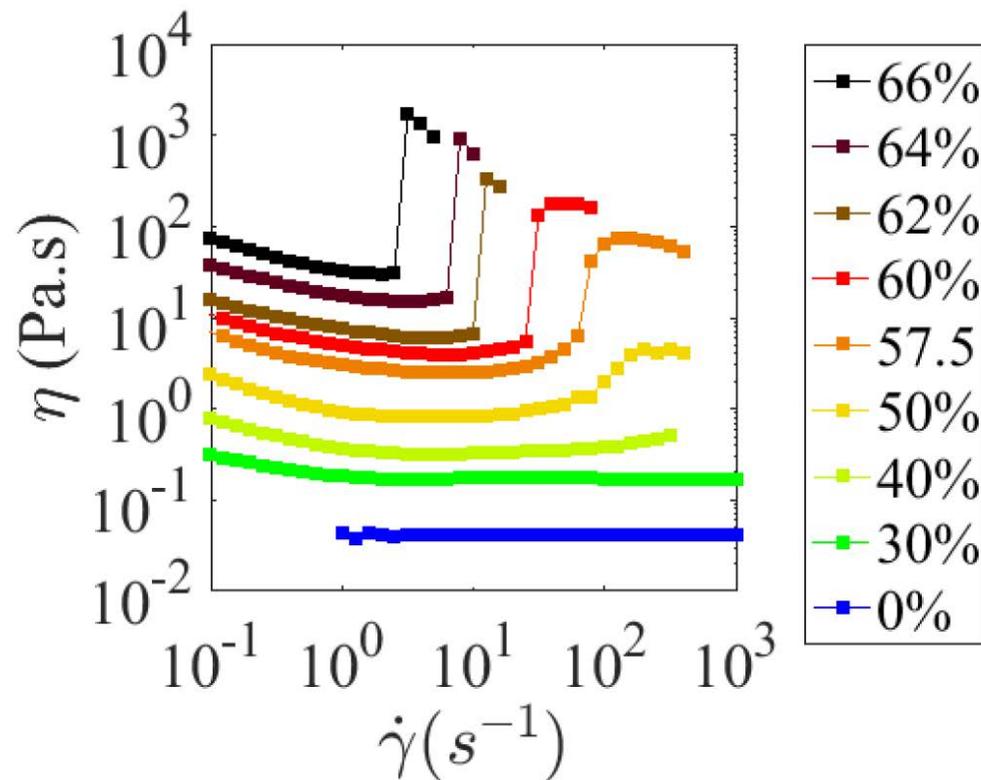


S Shape curve  
Instable flows  
Traveling Bands  
In the vorticity direction.  
Coexistence of a jammed and  
a flowing band in the gradient  
direction

*J. Morris, R Seto, R Mari, JF Morris, MM Denn 2013 PRL Cates ,  
Wyart 2015 PRL, Cates PRL 2018*

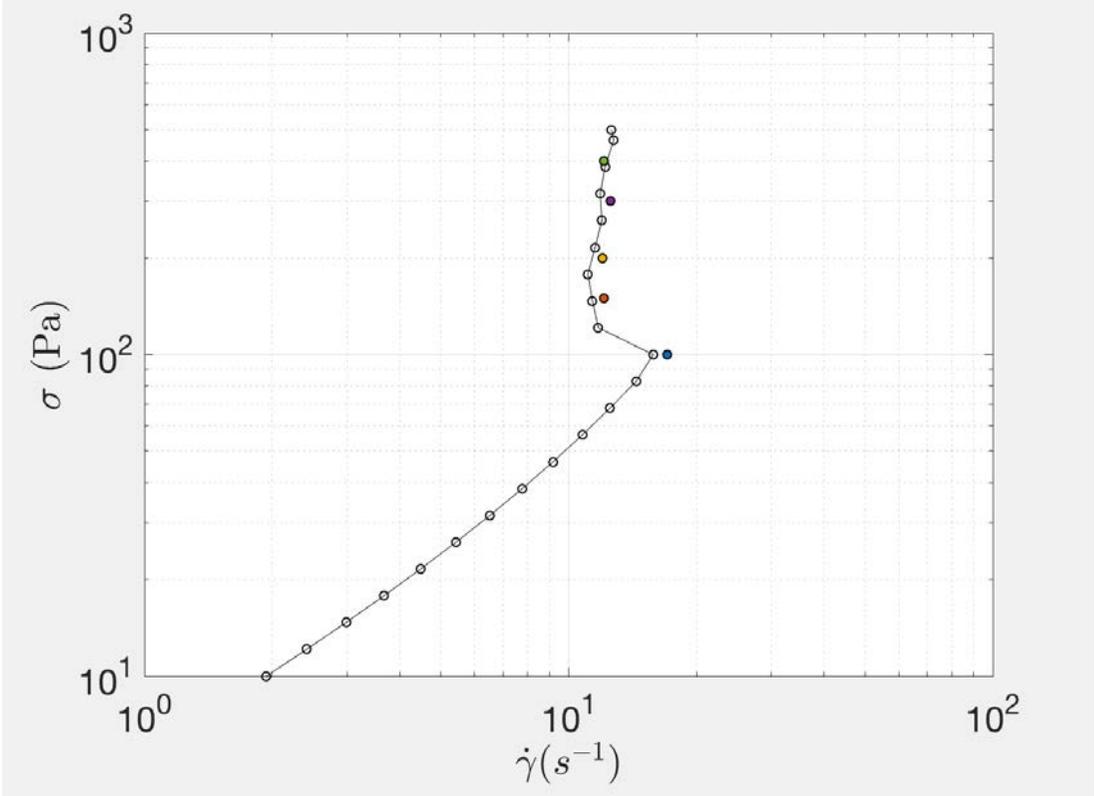
PVC –Dinch System,  
**Rheology**, the ST transition.  
Our study.

# Shear Thickening, under applied Shear Rate

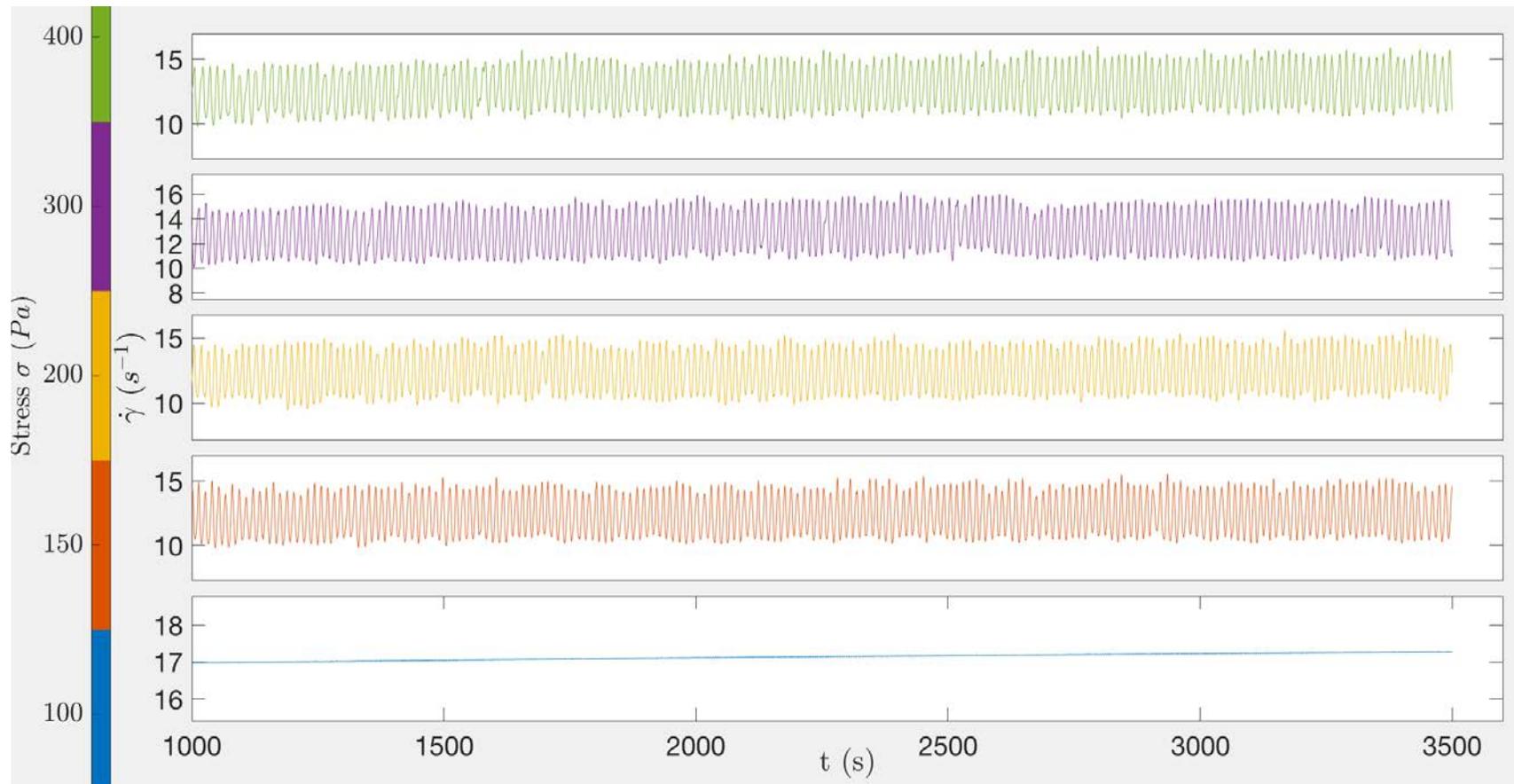


Under applied shear rate  
Couette Cell 1mm gap

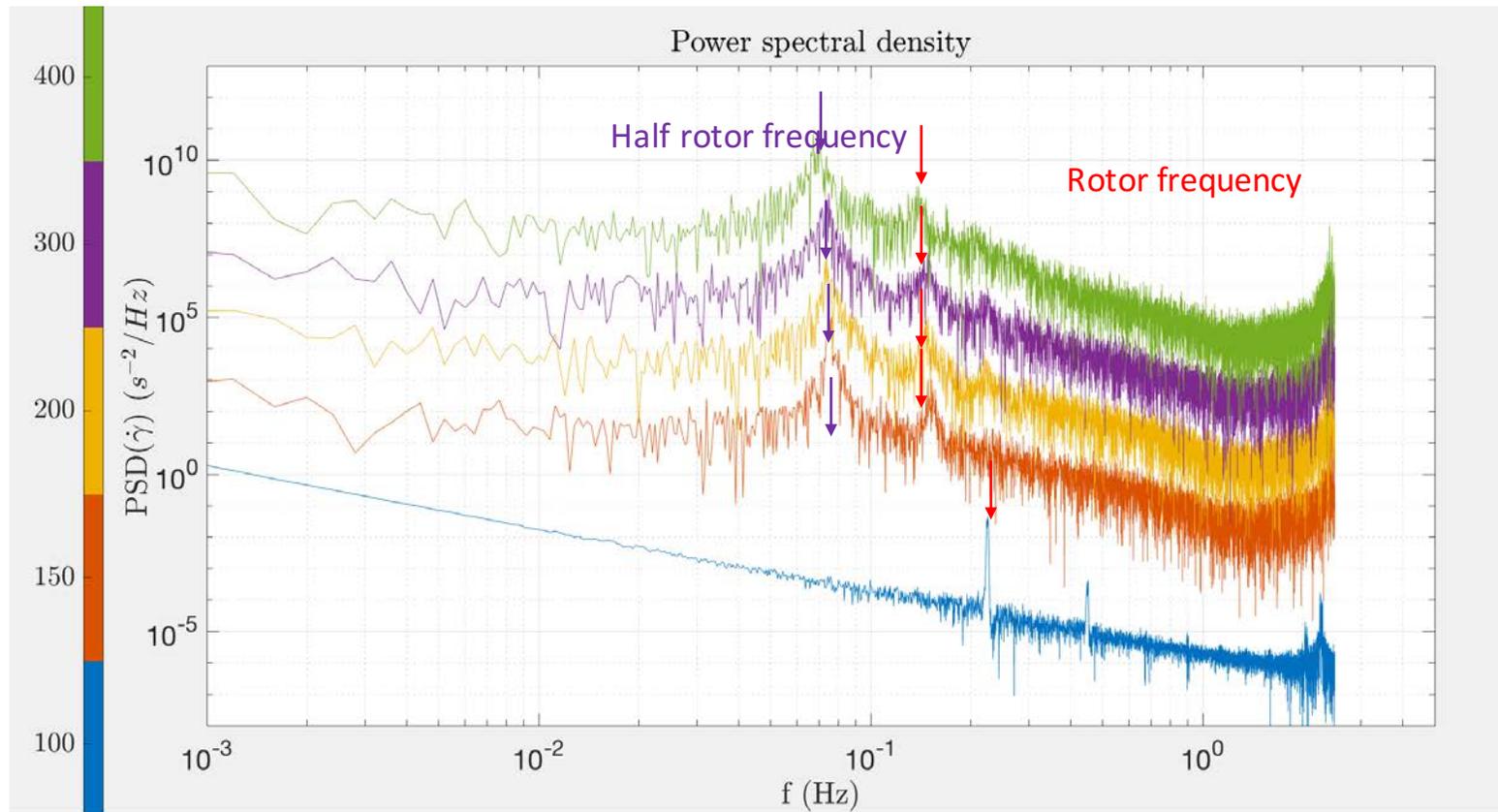
# Shear Thickening under Applied Shear Stress



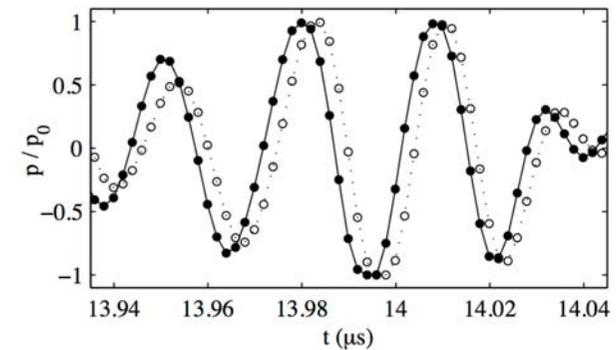
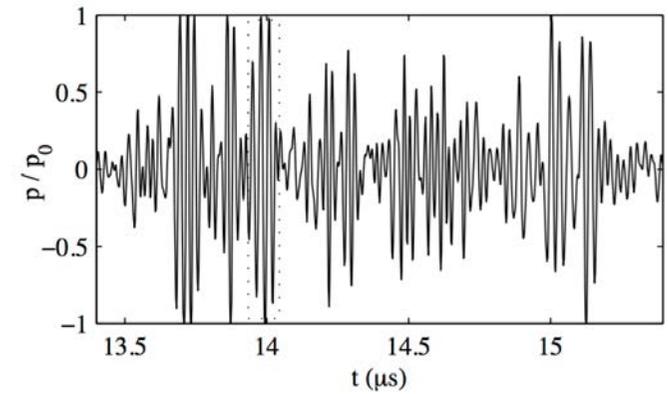
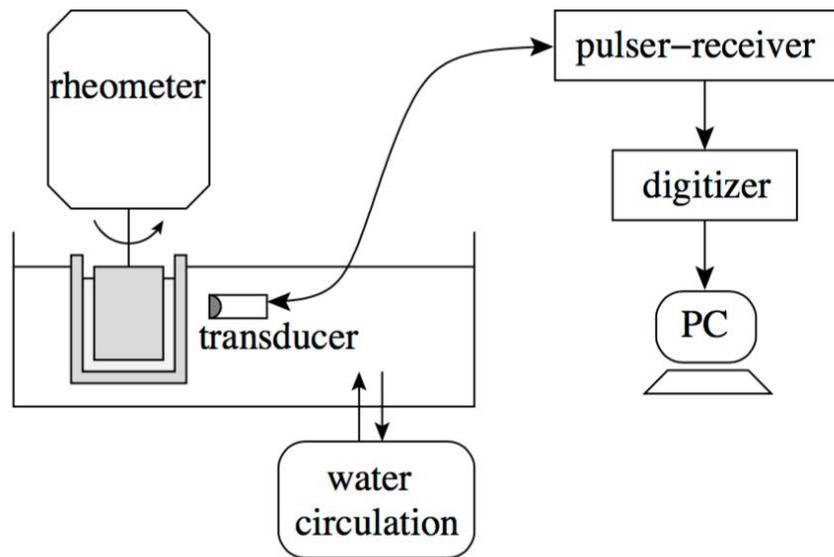
# Shear Thickening, under applied Shear Stress



# Shear Thickening under applied Shear Stress



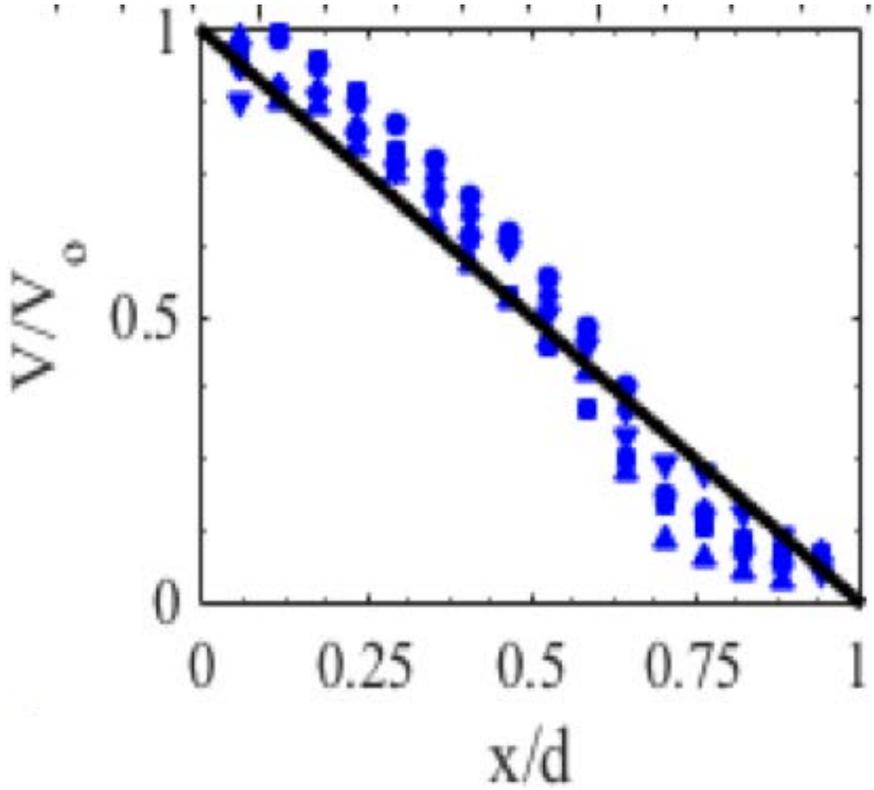
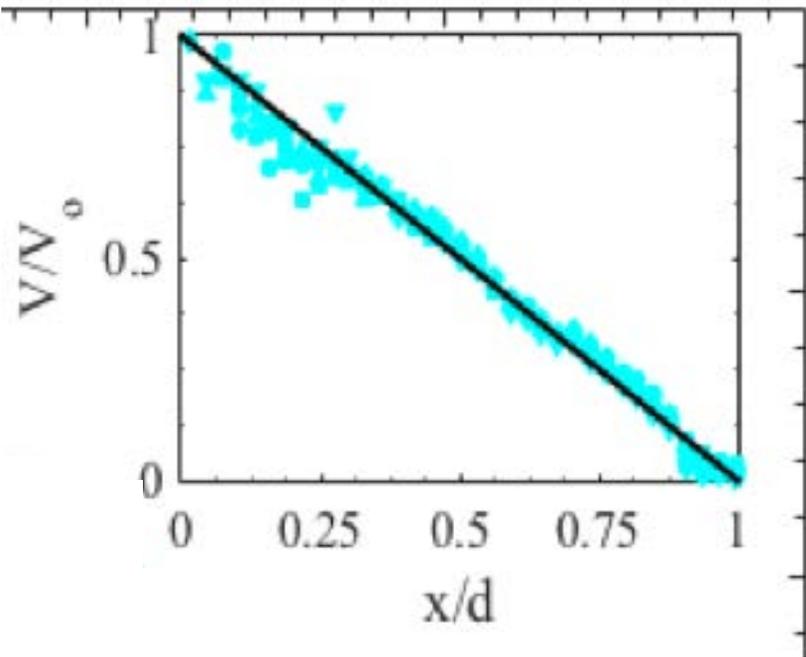
# How do suspensions flow? Velocity profiles measurements



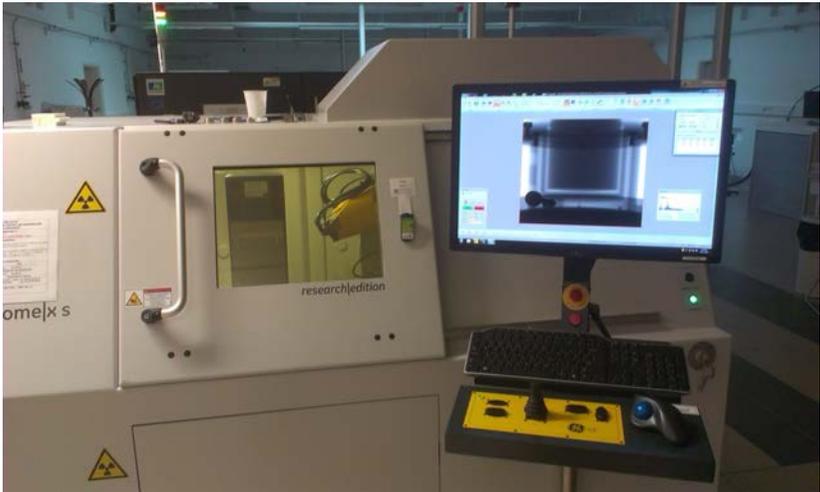
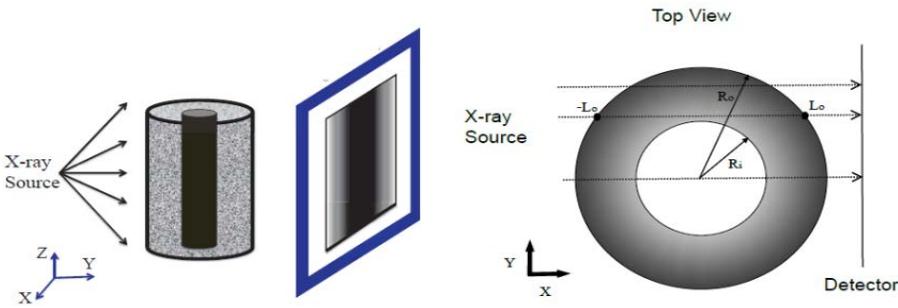
*S. Manneville, L.Bécu, and A. Colin EPJE 2003*

$$v = c_0 \frac{\delta t}{2T} \quad y = c_0(t_k - t_s)/2$$

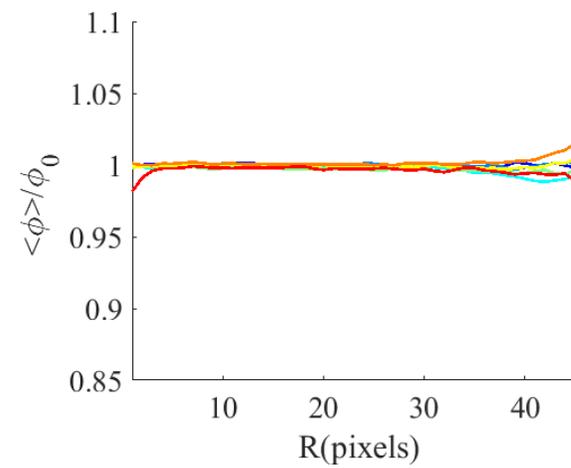
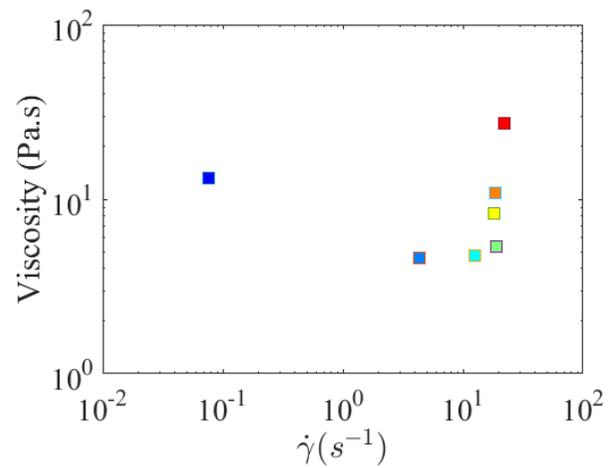
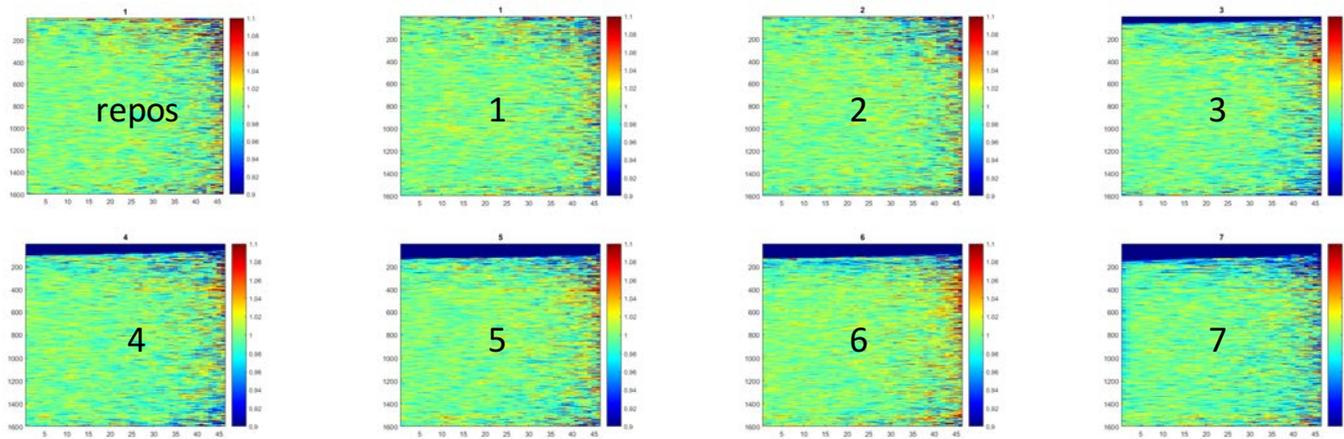
# Velocity profile homogeneous no slip



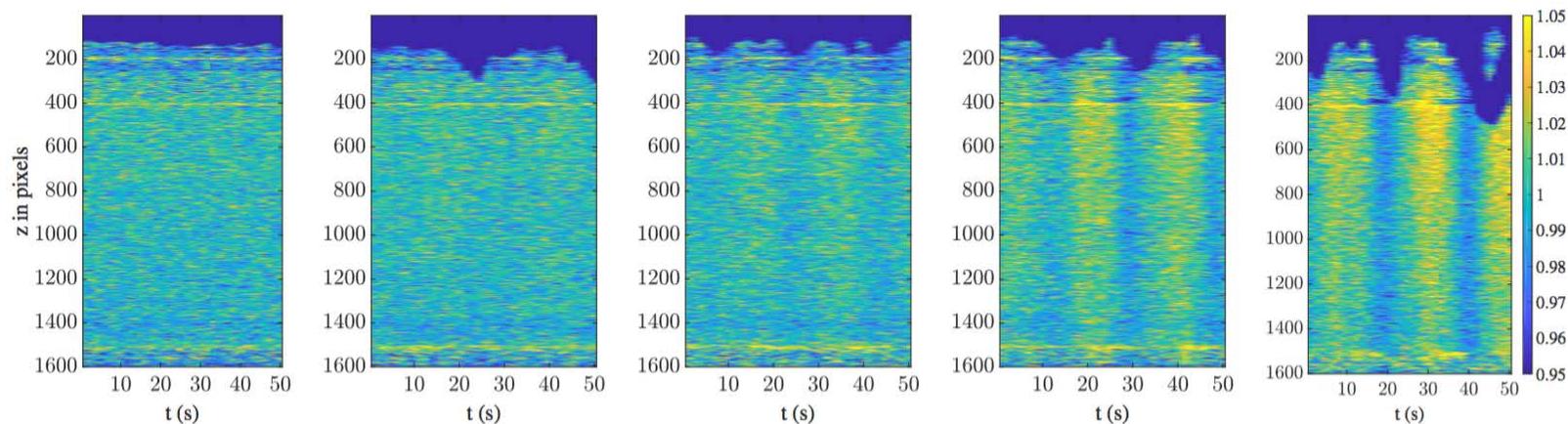
# Solid fraction profile



# PVC 1 mm gap No migration, no bands

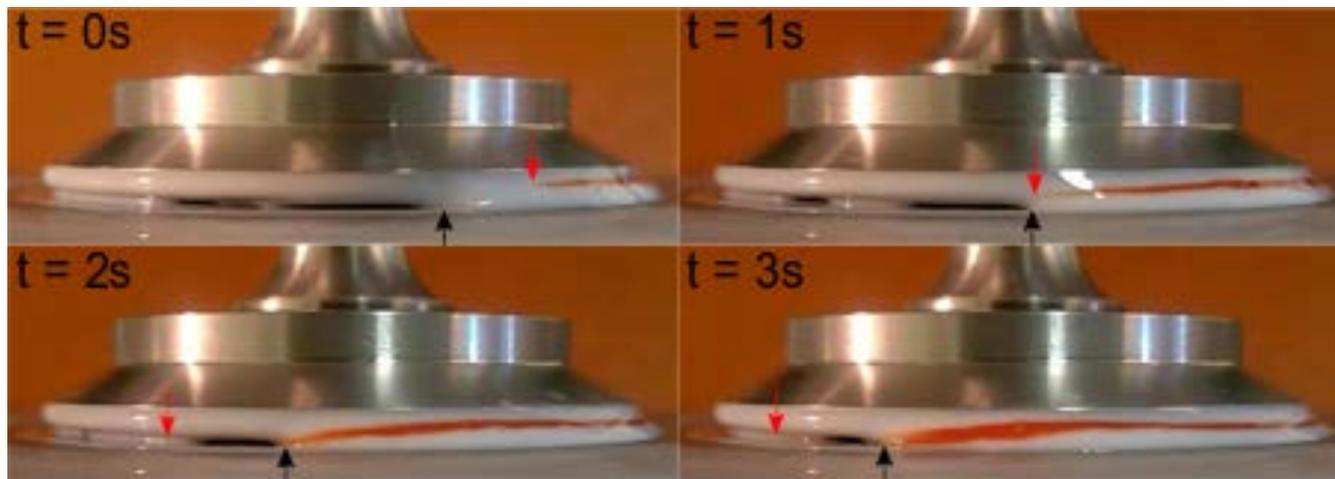


## PVC 1 mm gap



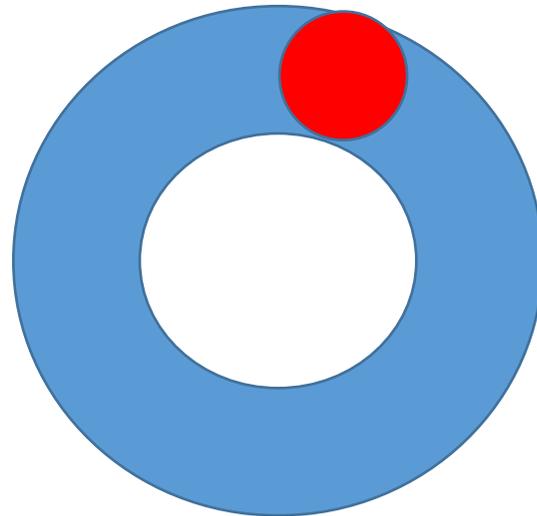
The solid fraction in the bands increases as a function of the shear stress.  
The bands have a velocity equal to half the velocity of the rotor

Feature of the flow : travelling bands



# Picture of the flow: band along the velocity

- The variation of the viscosity is due to a mis-alignment of the Couette cell.



# Conclusion and Outlooks

- Shear thickening a transition between lubricated contacts and solid friction.
- Measurement of the interactions (formulation)
- Measurement of the solid fraction
- Traveling Bands along the flow direction.
- Modeling?
- Other suspensions?
- Other mechanism for shear thickening

- We excite the tuning fork mechanically, using a piezo-dither glued close to the tuning fork. The piezo-dither induces mechanical vibration of the tuning fork through its holding support.
- The sensitivity at the resonance is directly proportional to the quality factor  $Q$ .

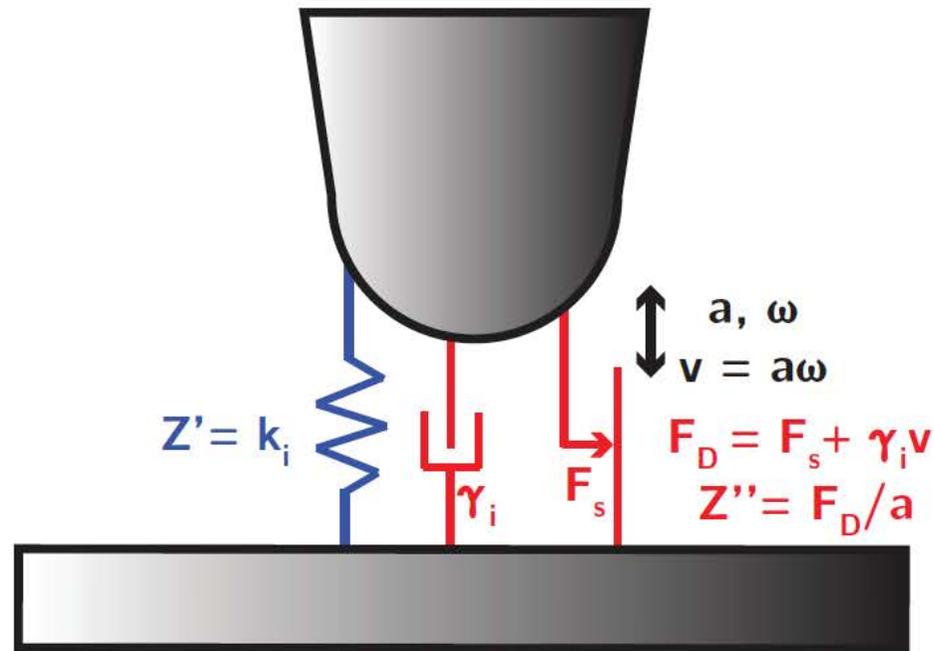


Figure 1.8: Tuning fork's tip oscillating at frequency  $\omega$  and amplitude  $a$ . The tip is interacting with a force field, modeled by a conservative part corresponding to a stiffness  $k_i$  or real mechanical impedance  $Z'$ , and dissipative part  $F_D$ , modeled by the sum of viscous like damping force  $\gamma_i \dot{x}$  and solid-like friction force  $F_s \dot{x}/|\dot{x}|$ , and characterized by the dissipative mechanical impedance  $Z'' = F_D/a$ .

One obtain thus a fundamental relation between the frequency shift  $\delta f = (\omega_i - \omega_0)/2\pi$  of the resonance, and the conservative interaction stiffness  $k_i$  or conservative impedance  $Z'$ , with:

$$Z' = k_i = 2K_{\text{eff}} \frac{\delta f}{f_0} \quad (1.20)$$

When all dissipative forces are of purely viscous type, the dissipative forces  $F_{\text{D}}$  and dissipative impedance  $Z''$  are directly related to the change in the quality factor from  $Q_0$  to  $Q$ , via

$$Z'' = \frac{F_{\text{D}}}{a} = K_{\text{eff}} \left( \frac{1}{Q} - \frac{1}{Q_0} \right) \quad (1.22)$$

One can thus directly measure the sum of all dissipative forces (viscous or not) via the measurement of the external excitation force necessary to apply on the tuning fork to keep a constant oscillation amplitude  $a_0$ . This excitation force  $F_{\text{ext}}$  is directly proportional to the excitation voltage  $E$  of the piezo-dither, via:

$$Z'' = \frac{F_{\text{D}}}{a_0} = \frac{K_{\text{eff}}}{Q_0} \left( \frac{E}{E_0} - 1 \right) \quad (1.24)$$

- The tuning forks are commercially available (Radiospare). They are stored under controlled atmosphere in a shell. The first step is to get the tuning fork out of its shell.
- The second step is the gluing of the tip to one of the prong of the tuning fork (typically tungsten or gold).
- To etch the tungsten tips, a drop of 1 M NaOH in each ring creates an electrolytic cell in which the tungsten wire is etched.

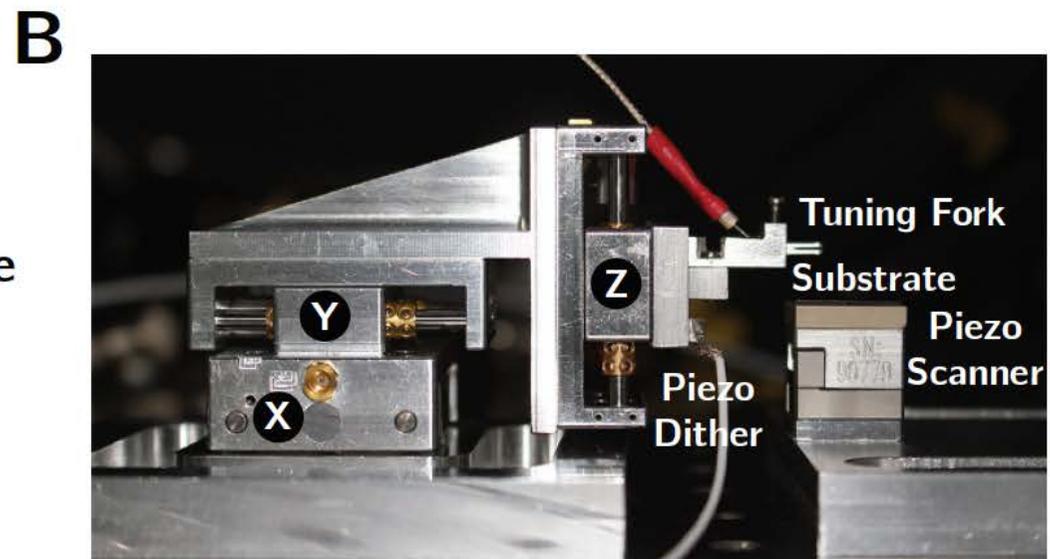
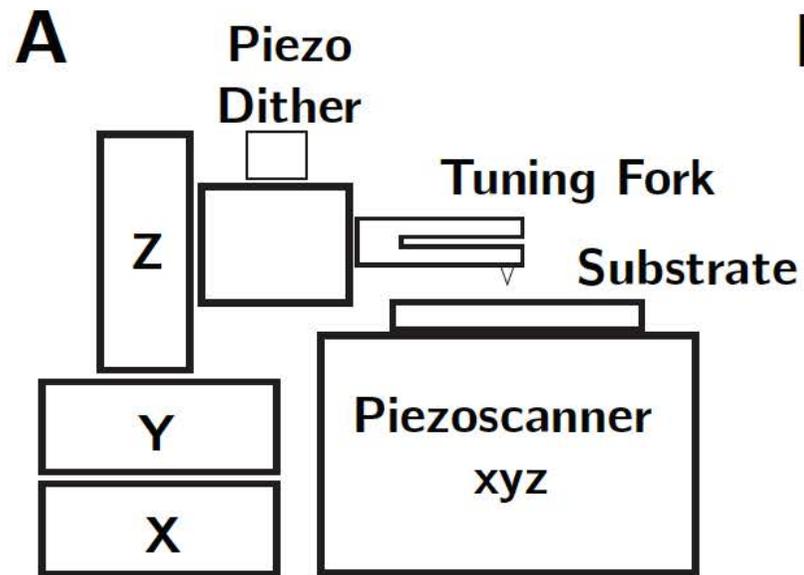


Figure 1.11: Schematic of the AFM set-up, with coarse positioning motors (X, Y, Z), a 3-axis piezoelectric scanner (xyz), the tuning fork, substrate and piezo dither.

# Detection of phase shift amplitude

- The piezoelectric current generated by the oscillation of the tuning fork is amplified using a commercial femto preamplifier (DLPCA-200), typically with a gain of  $10^7$  V/A, corresponding to a 50 kHz bandwidth. Frequency-modulation AFM techniques are implemented using a Phase Locked Loop, allowing to systematically excite the tuning fork at its resonant frequency. The shift in resonance frequency gives a direct measurement of the conservative force field applied on the tuning fork. The excitation of the piezo dither, i.e. the external force applied on the tuning fork is adjusted by an additional PID servo loop, to maintain a constant oscillation amplitude at the resonance. This excitation voltage gives a direct measurement of the dissipative forces applying on the tuning fork.

- The outputs of the lock-in are the amplitude of oscillation  $a$  [m] and the phase shift
- [rad] of the tuning fork oscillation  $a(t)$  with respect to the excitation voltage  $E(t)$  at
- the excitation frequency !.