Business from technology

Rheological characterization of complex fluids using Multi Scale Velocity Profile measurements

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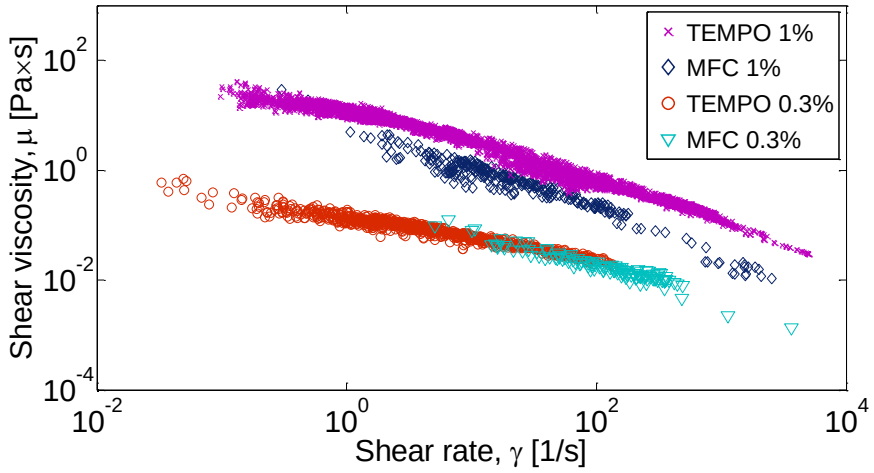
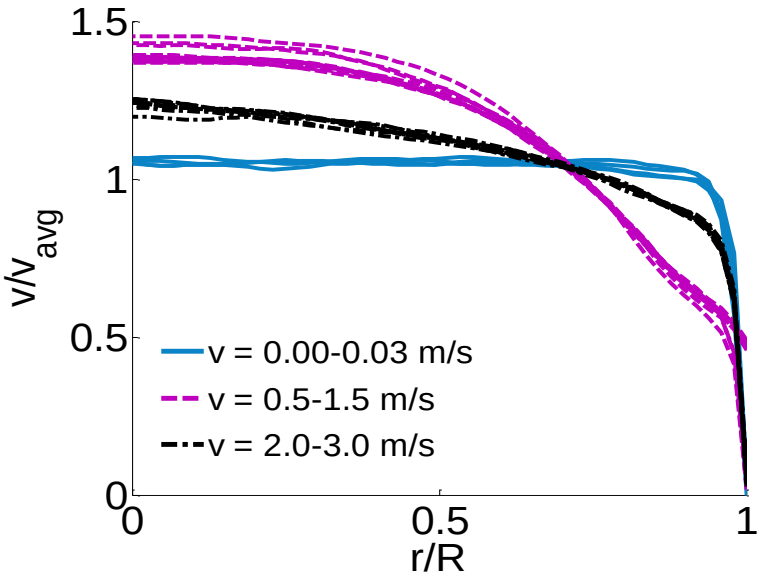
Background: Pipe Rheometry

- Characterization of the rheological behavior of cellulose suspensions, e.g. microfibrillated cellulose suspensions

- Recently pipe rheometer has been used to study MFC/NFC suspensions
  - Pressure drop and velocity profile
  - Different flow regimes and size of the plug flow region
  - Viscosity and yield stress

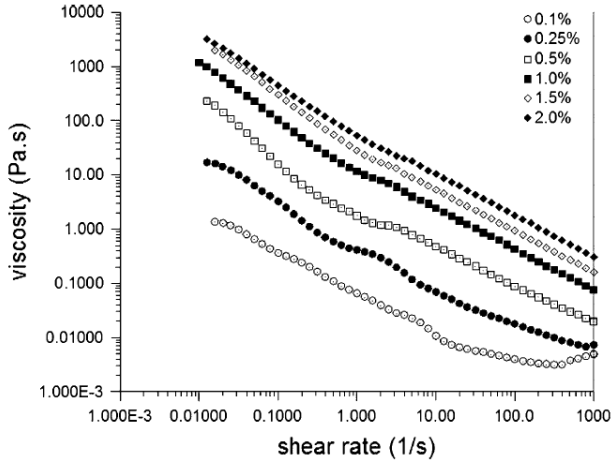


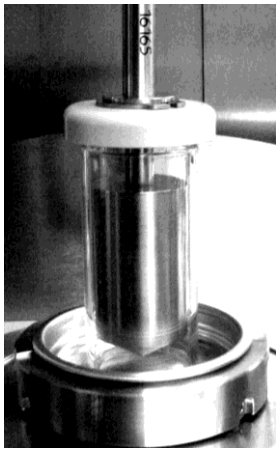


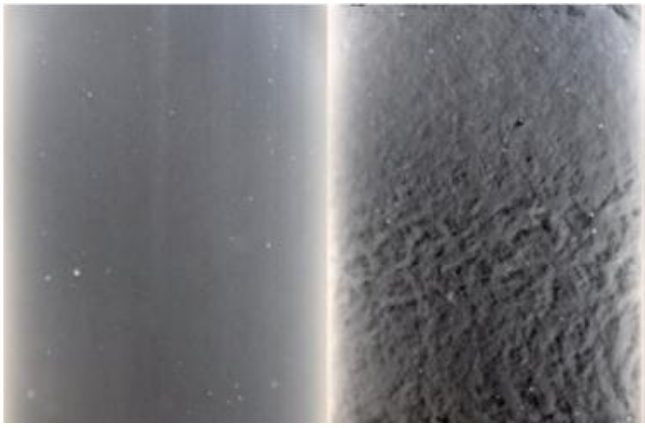
Motivation

1. Using previous measurement technique velocity profile in the close proximity of the pipe wall remained unclear

2. At which conditions traditional rheometers can be used to study MFC/NFC properties?
   - What is the flow profile and structure inside a rheometer gap?
   - Are the general assumptions valid?







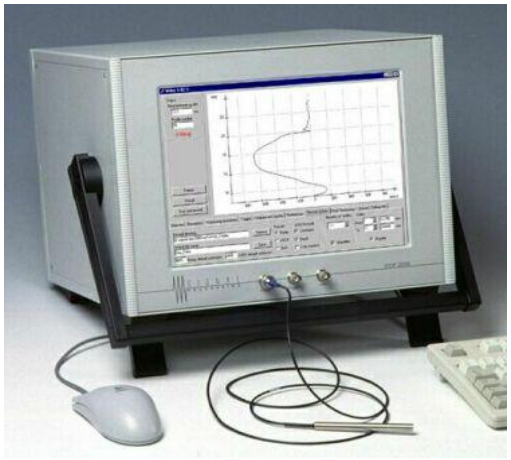
Sources: Karppinen et.al. / Cellulose 2012 and Saarikosko et.al. / Cellulose 2012

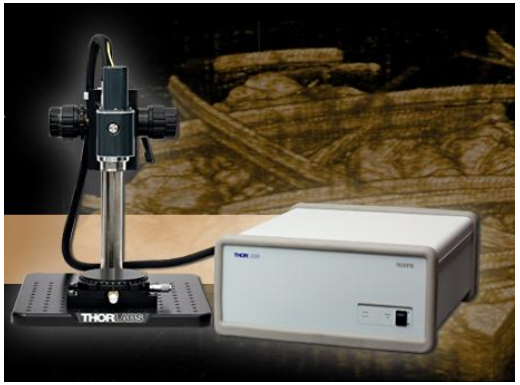
Rheology in Pipe Flow:

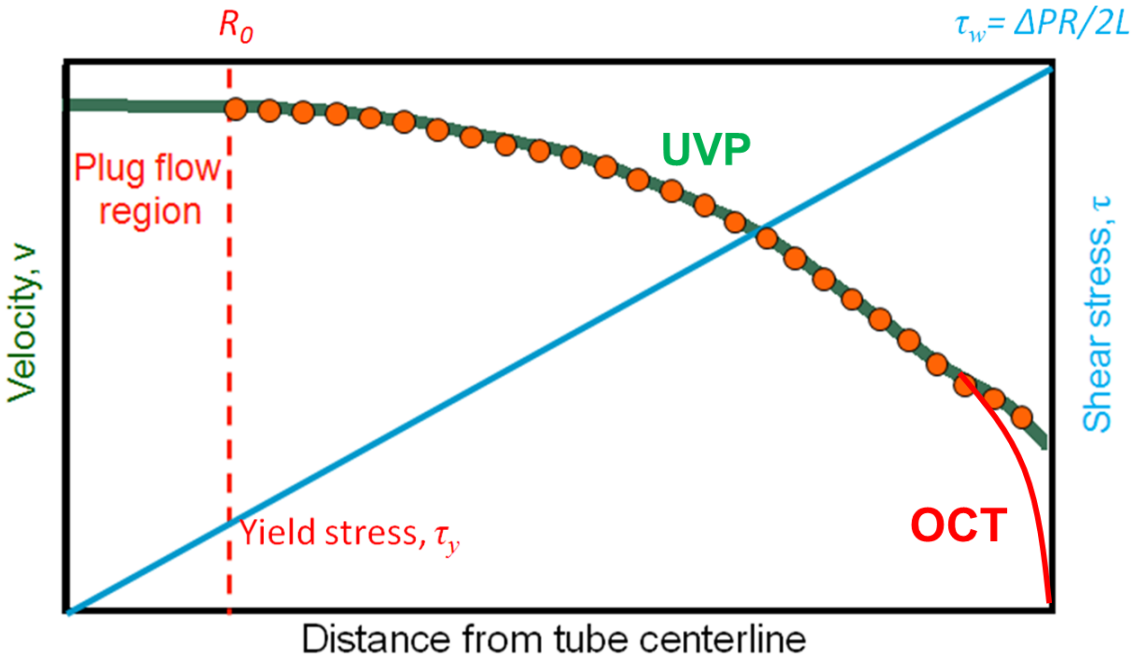
METHODS

Local viscosity: UVP-PD method and OCT

- The velocity profile is measured using Pulsed Ultrasound Doppler Velocity Profiling (UVP) and Optical Coherence Tomography (OCT)







Local shear stress: $\tau(r) = \tau_W (1 - r/R)$

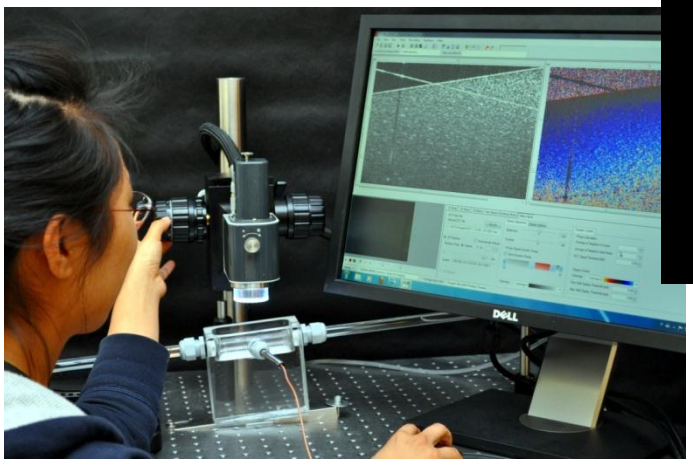
Local shear rate: $\dot{\gamma}(r) = dv/dr$

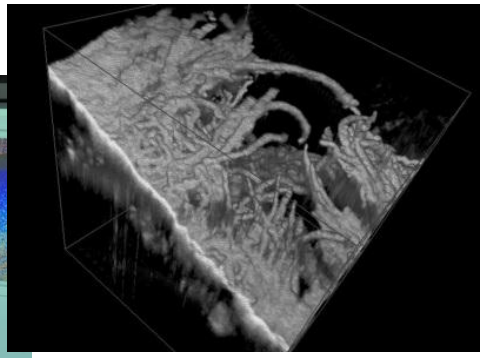
Local viscosity: $\mu(r) = \tau(r)/\dot{\gamma}(r)$

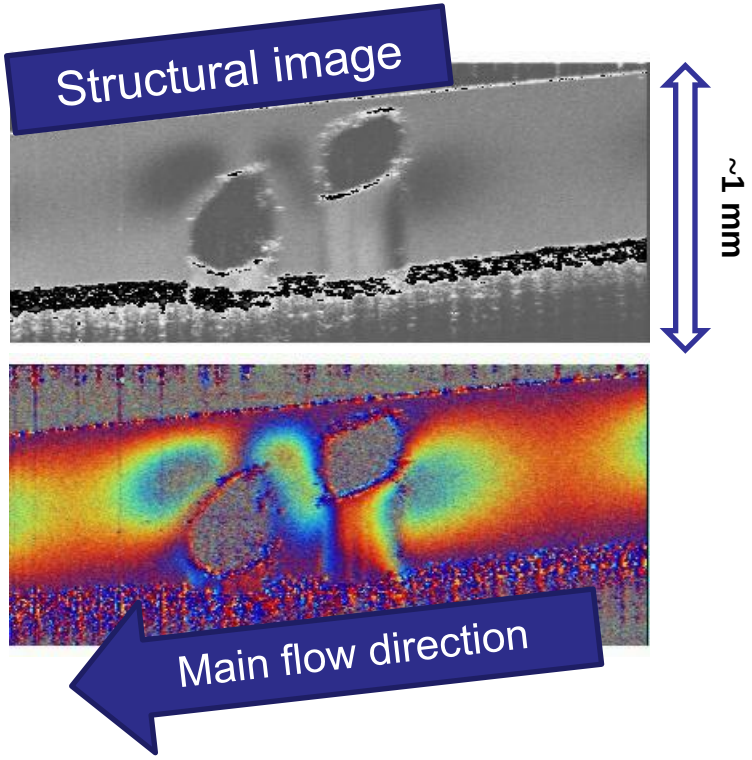
Yield stress: $\tau_y = \tau_W (1 - R_0/R)$

Optical Coherence Tomography

- A noninvasive optical imaging technique
- Based on low coherence interferometry
- Structural data and velocity data in an opaque scattering medium
- Micron-level resolution and millimeter scale imaging depth. Lateral imaging area 10x10 mm.

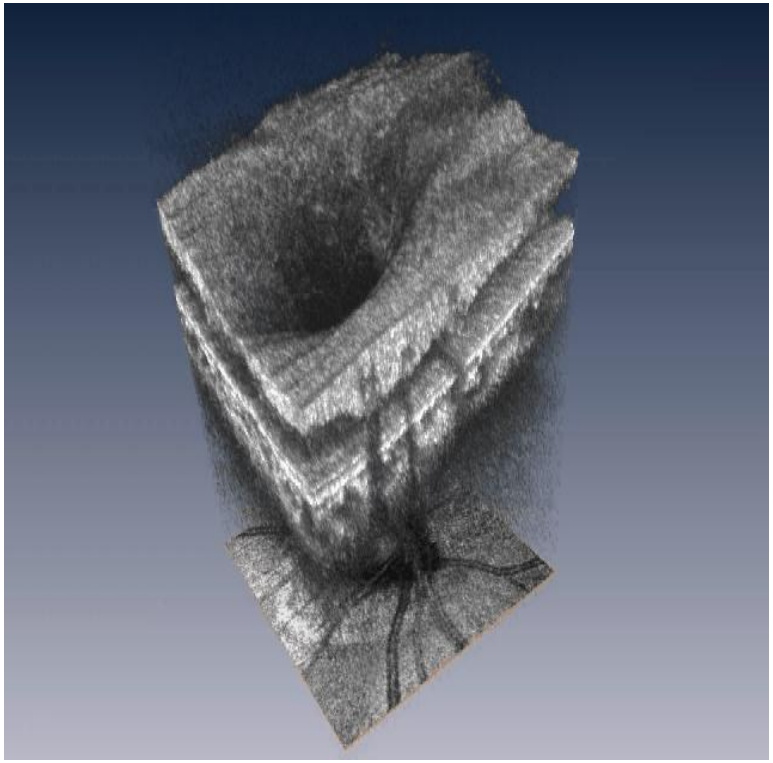






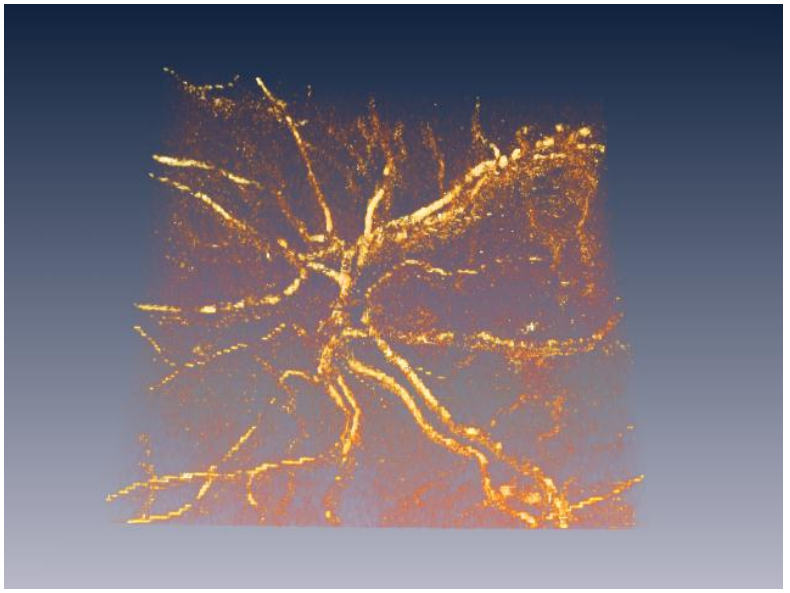
Structure and Doppler image of flow around spacer threads inside a filter geometry showing static vortices.

Optical Coherence Tomography



Volumetric image around optic nerve head

Source: Vol. 16, No. 12 / OPTICS EXPRESS



Volumetric vasculature image

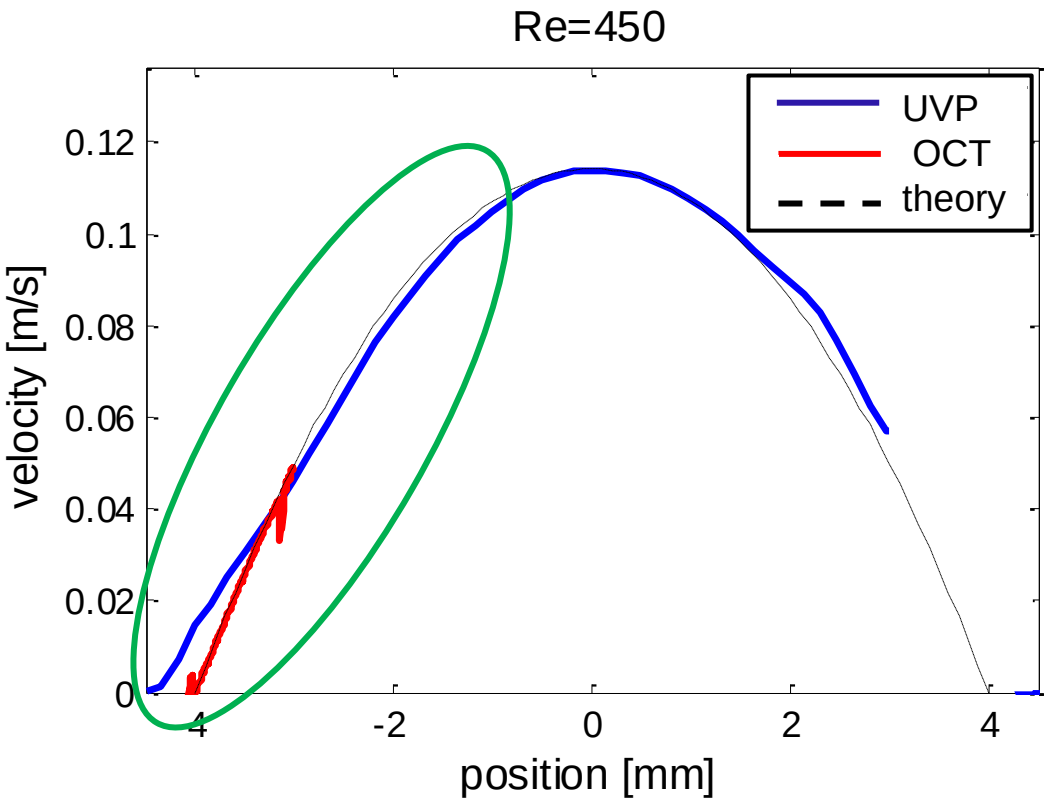
Source: Vol. 14, No. 17 / OPTICS EXPRESS

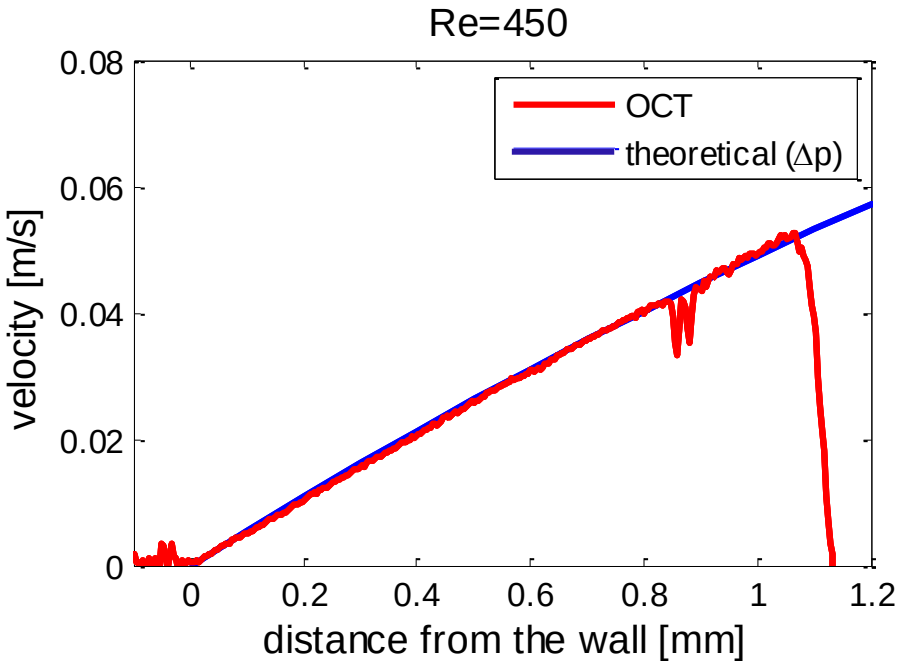
Rheology in Pipe Flow:

VERIFICATION MEASUREMENTS

Verification of UVP and OCT: laminar Newtonian flow

- tap water (and some tracer particles for UVP)
- pipe diameter 8.0 mm





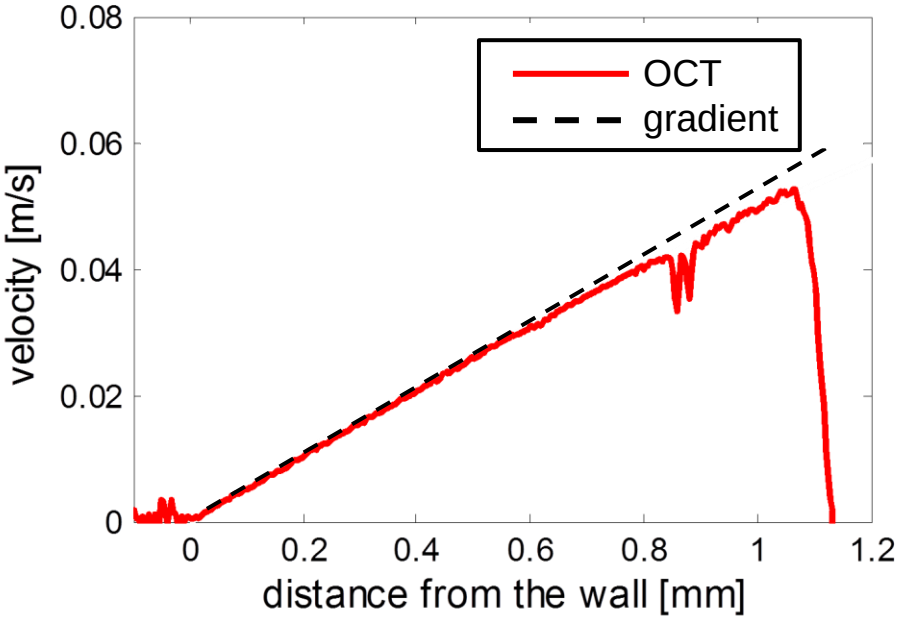
Verification of OCT: laminar and turbulent Newtonian flow (water)

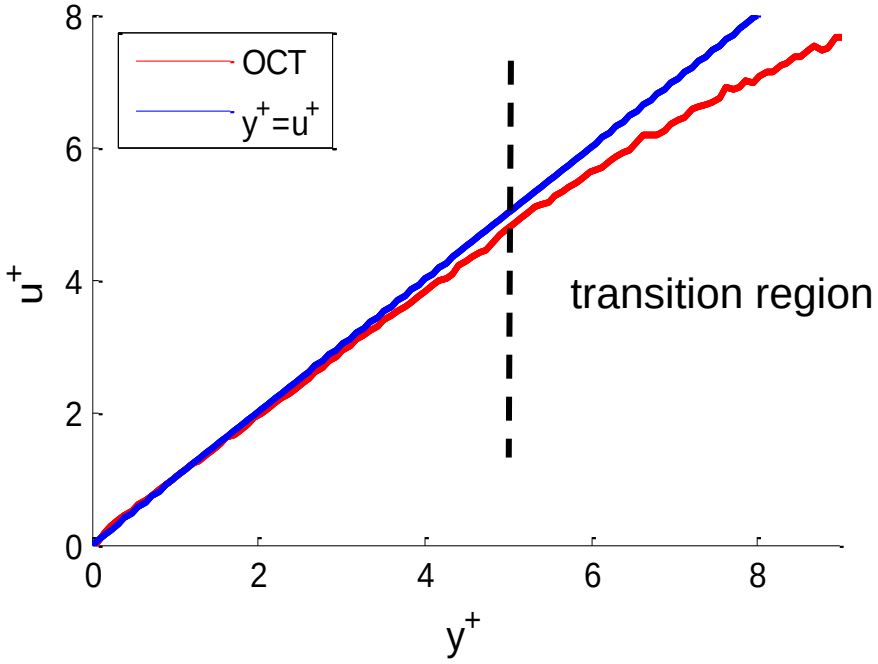
Wall friction:

$$\tau_{OCT} = \mu_{\text{water}} \left(\frac{dv(r)}{dr} \right)_{r \to R}$$

Pressure loss:

$$\Delta p_{OCT} = \pi D L \tau_{OCT}$$





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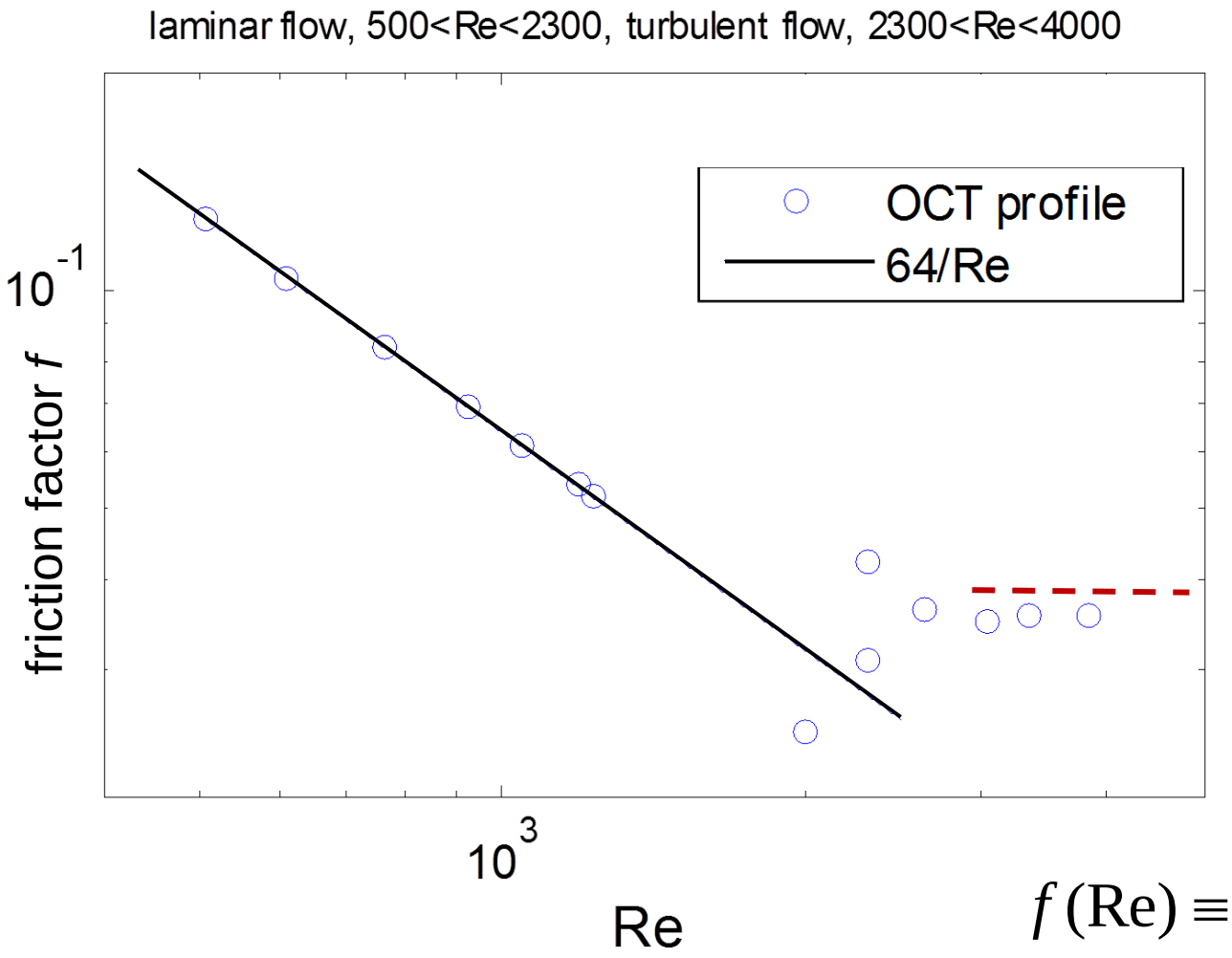
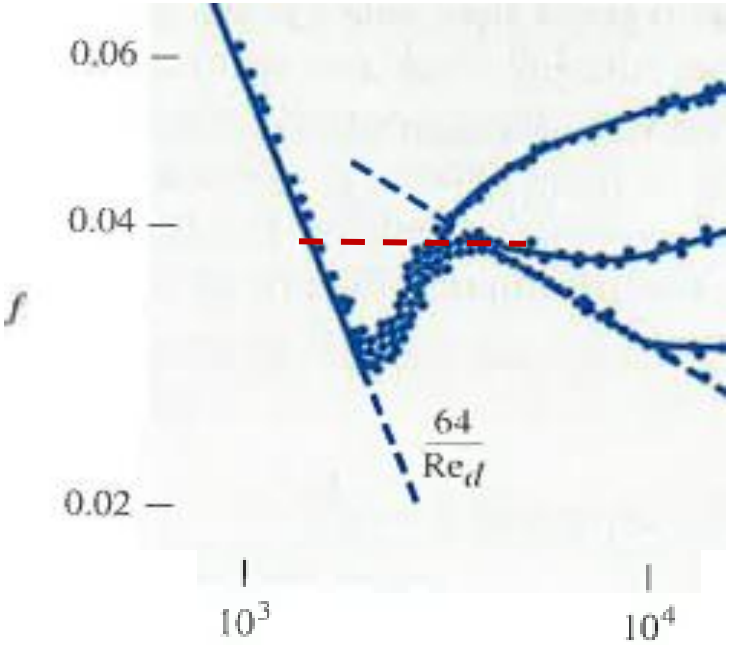


Friction factor:

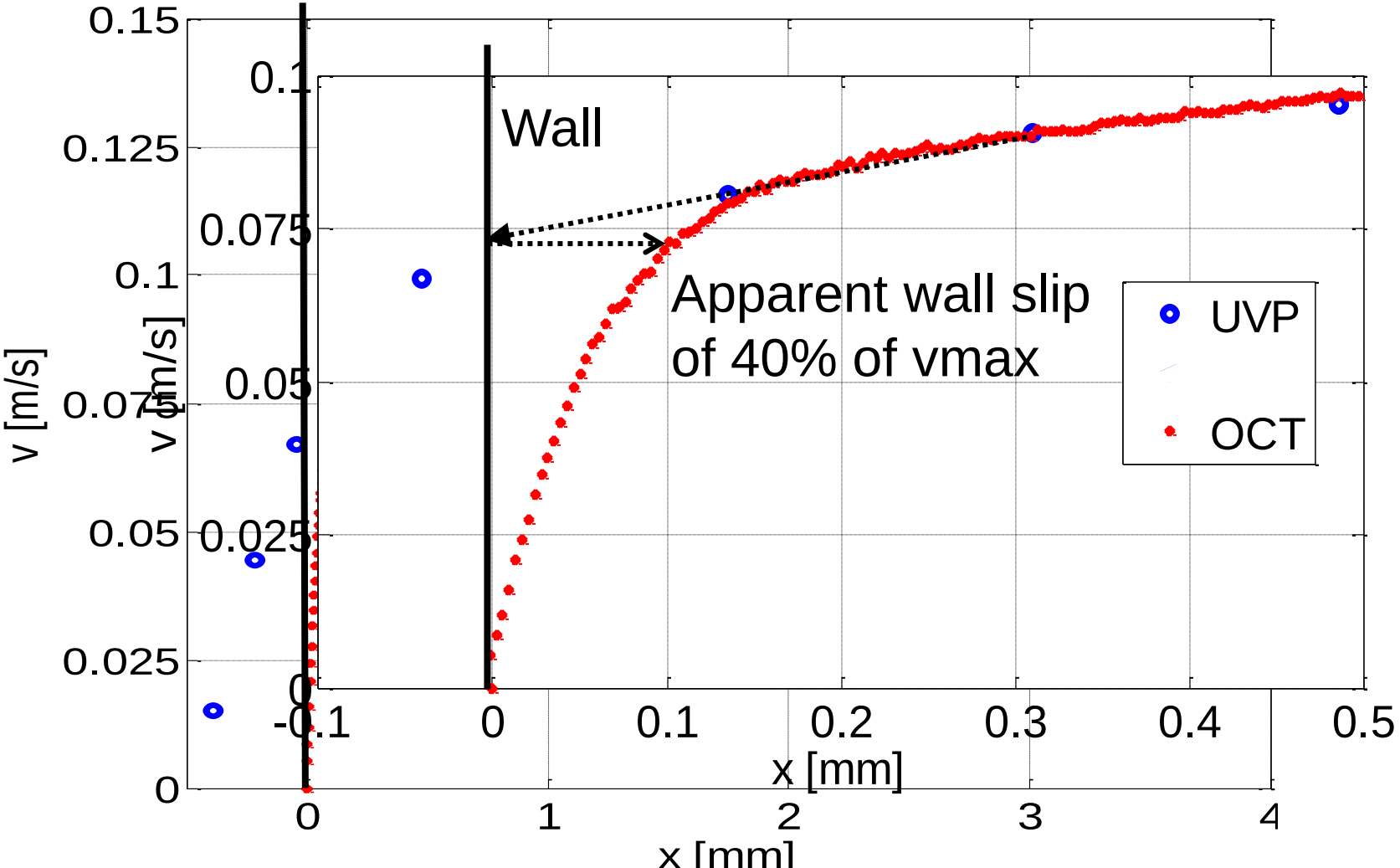


$$f(\mathrm{Re}) \equiv \Delta p_{OCT} \Big/ \frac{L}{D}\frac{\rho V^2}{2}, \mathrm{Re} = \frac{\rho V D}{\mu}$$

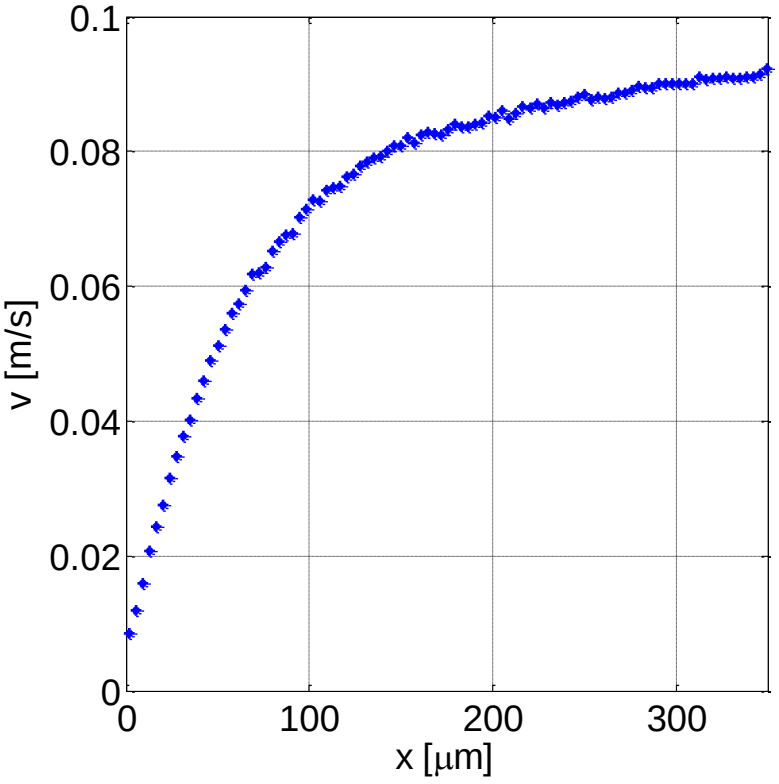
Rheology in Pipe Flow:

FLOW NEAR THE WALL

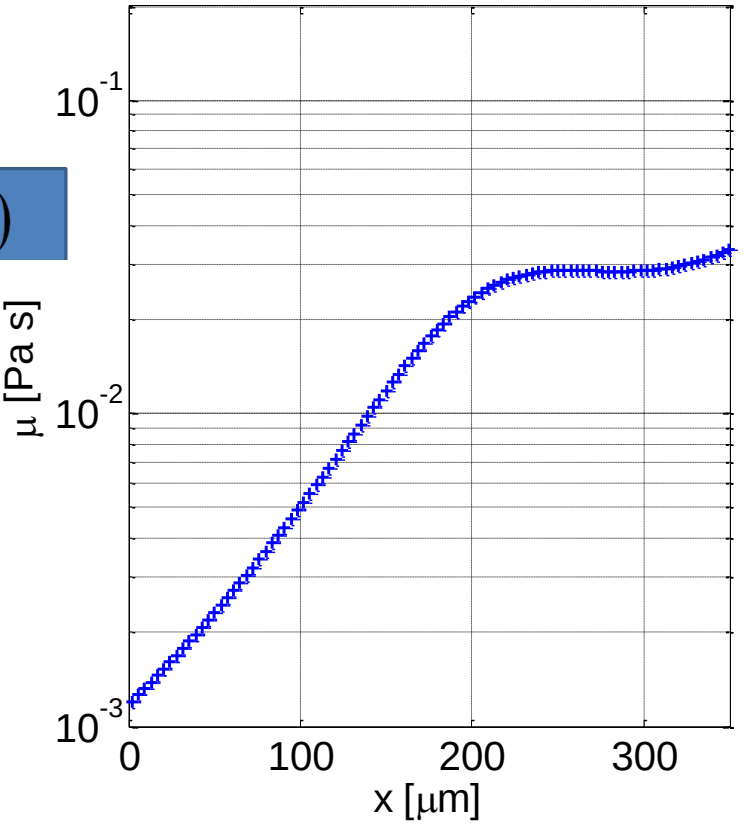
MFC flow profile results
Velocity



MFC flow profile results
Viscosity

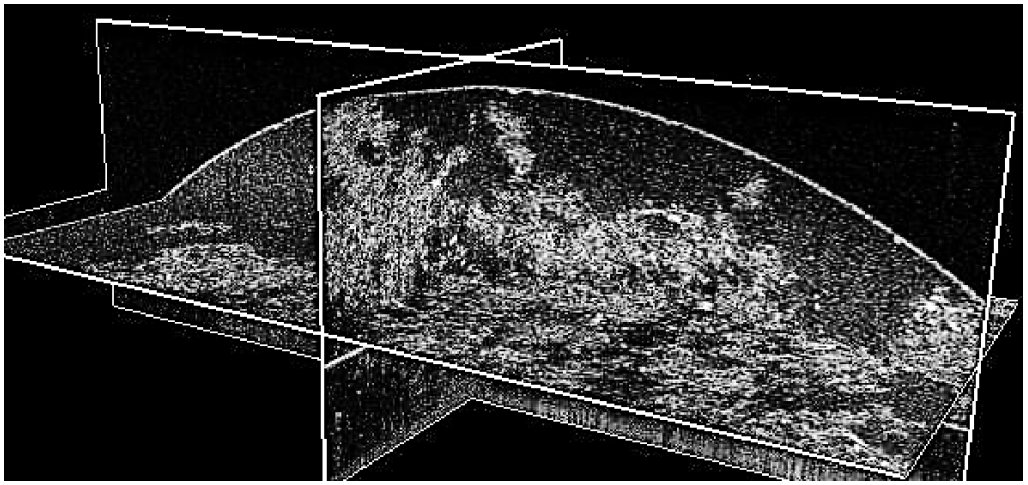


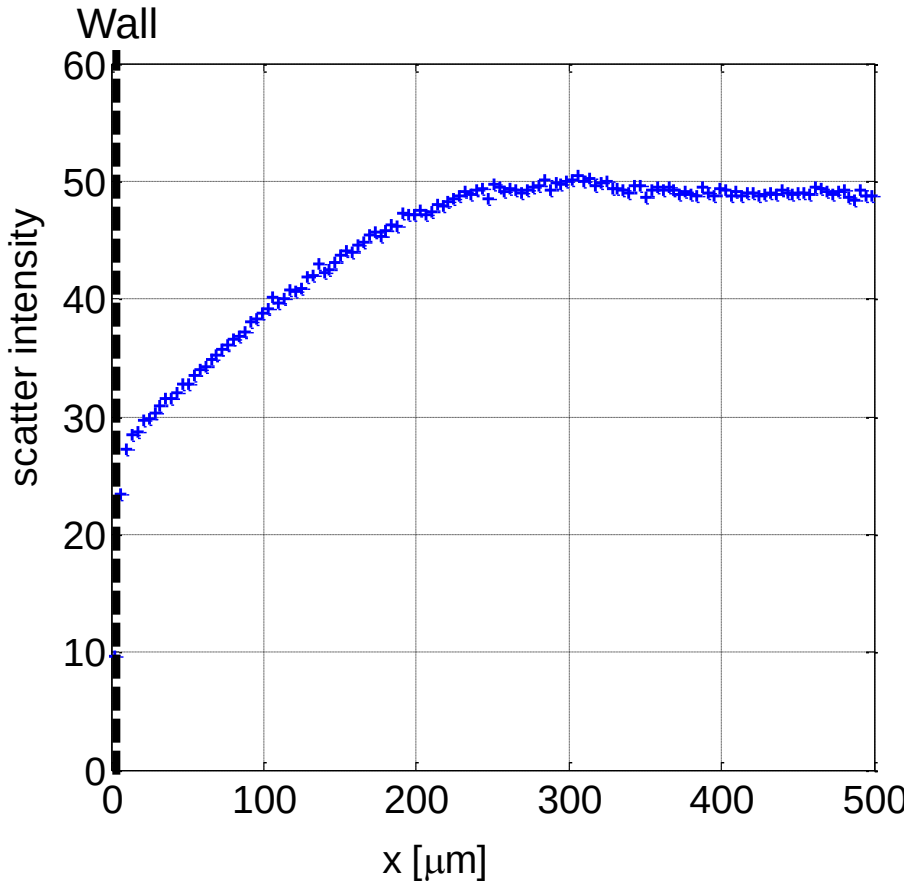
$$\mu(r) = \tau(r)/\dot{\gamma}(r)$$



MFC flow profile results
Consistency

3D OCT image of micro fibrillated cellulose in the pipe



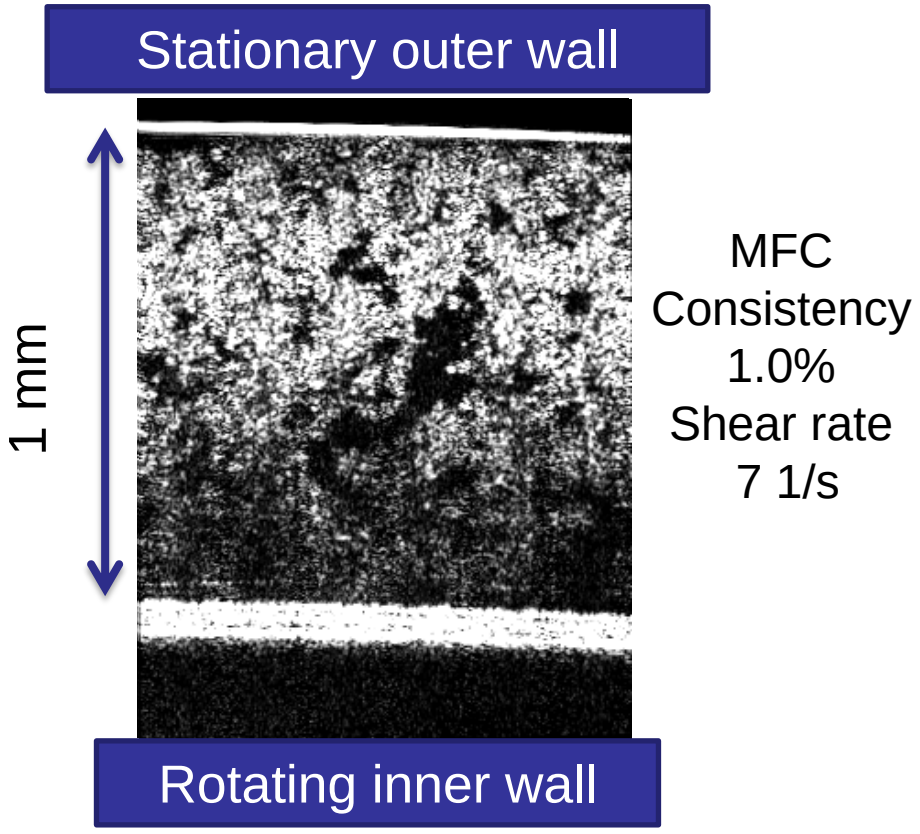


FLOW INSIDE A ROTATIONAL RHEOMETER

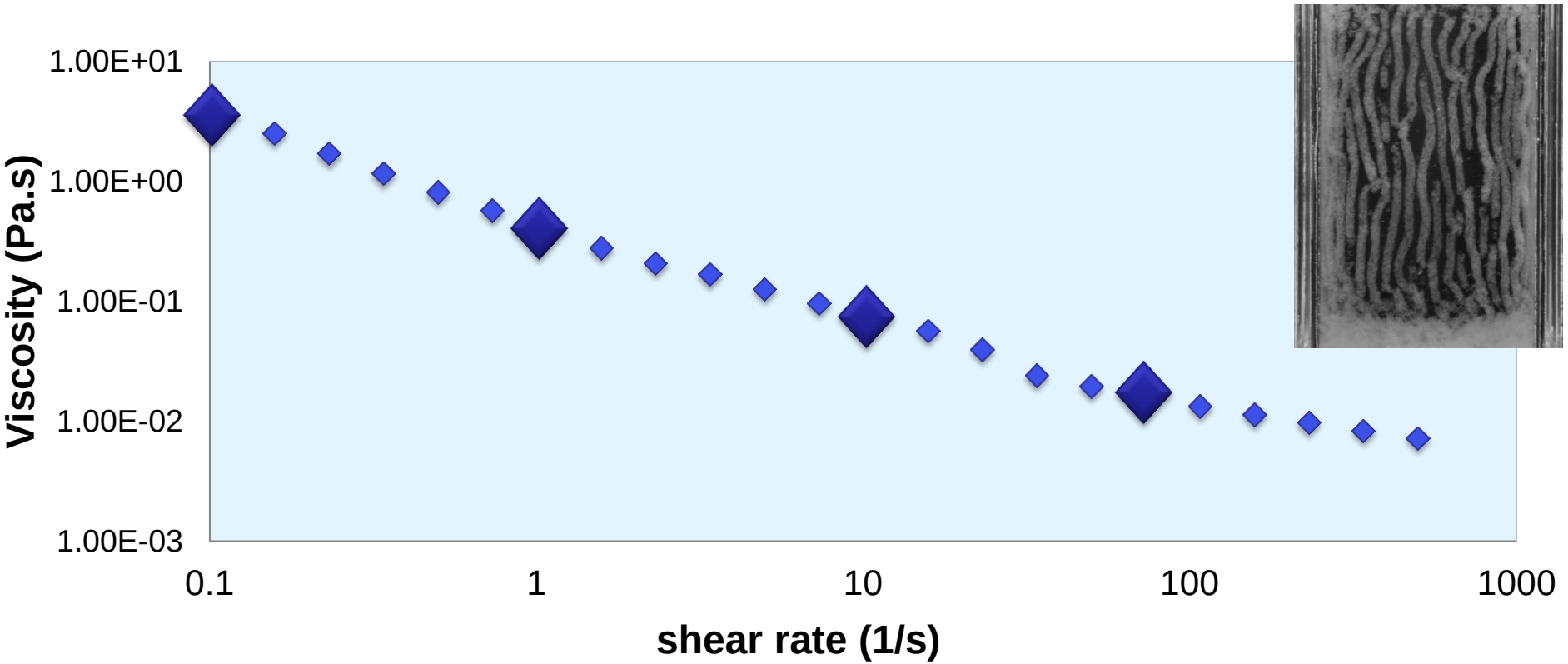
Flow inside the rheometer

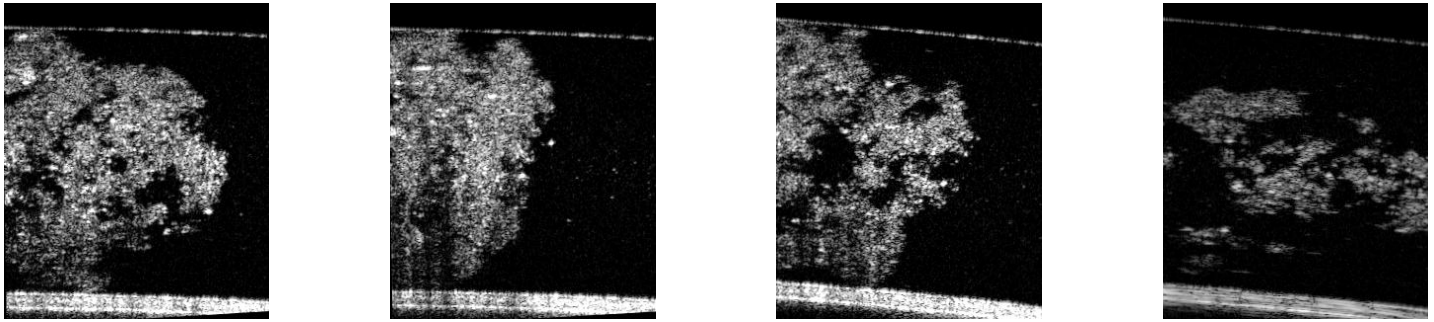
- Cocentric cylinders geometry (bob and cup)
- Transparent outer geometry

- Observations:
  - Extremely complex shear field
  - Rollers near the walls
  - Compression due to roller formation
  - Plug flow
  - Slip



Coarse grade microfibrillated cellulose (c=0.4%)





Conclusions

- New **OCT** measurements extend the velocity profile measurement to the boundary layer of opaque suspensions.
  - Simultaneous measurement of the structure and velocity with high spatial and temporal resolution
    - Possibility to measure both solid phase velocity and fluid velocity
  - Several applications including e.g. fibre and polymer suspensions, blood flow, foam flow

- This