

Experimental studies of turbulent Taylor-Couette flow : single phase and liquid-liquid dispersions.

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Aims of our study

Two immiscible fluids (oil and water), mixed in a turbulent flow, with no surfactants.

Subtle balance between turbulent **breakup** and **coalescence**

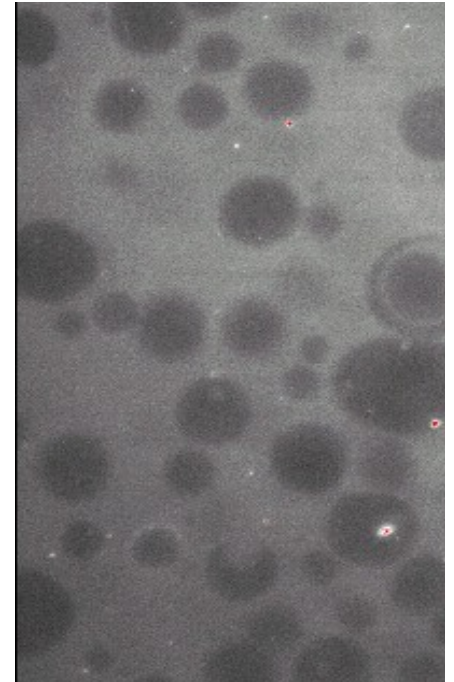
Oil extraction, food, chemical industry



Turbulent dispersion

Droplet size distribution,
Phase inversion.

Modified transport properties
(drag increase in pipe flow)



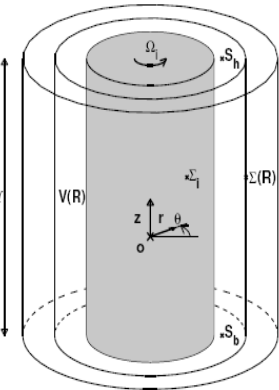
Conception and **design** of a new experiment which allows

- Optical measurements (LIF and PIV) in a two phase-flow
- Global power consumption measurements.

A **model shear-flow** : **the turbulent Taylor-Couette flow**

Single-phase Taylor-Couette flow

Coaxial rotating cylinders



Geometry

$$d = r_o - r_i : \text{Gap}$$

$$\eta = r_i / r_o : \text{Gap ratio}$$

$$\Gamma = h / d : \text{Aspect ratio}$$

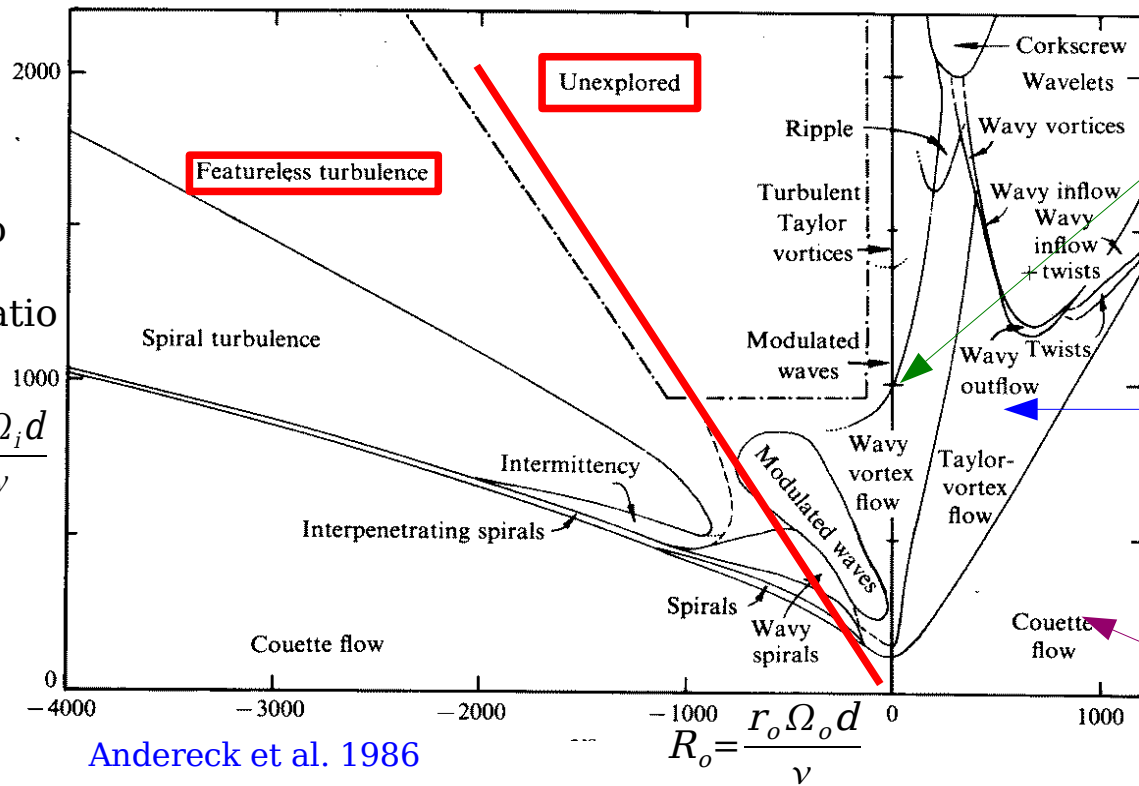
$$R_i = \frac{r_i \Omega_i d}{\nu}$$

Kinematic parameters

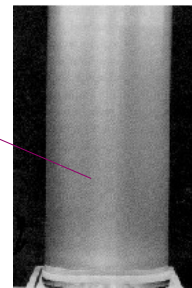
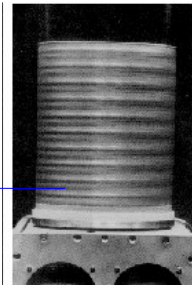
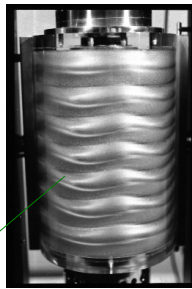
Ω_i Inner cylinder ang. velocity

Ω_o Outer cylinder ang. velocity

ν Kin. viscosity



Andereck et al. 1986



Dynamics motivated choice of parameters

Reynolds number : $R_e = \frac{2}{1+\eta} |\eta R_o - R_i|$

Rotation number : $R_\Omega = (1-\eta) \frac{R_i + R_o}{\eta R_o + R_i}$

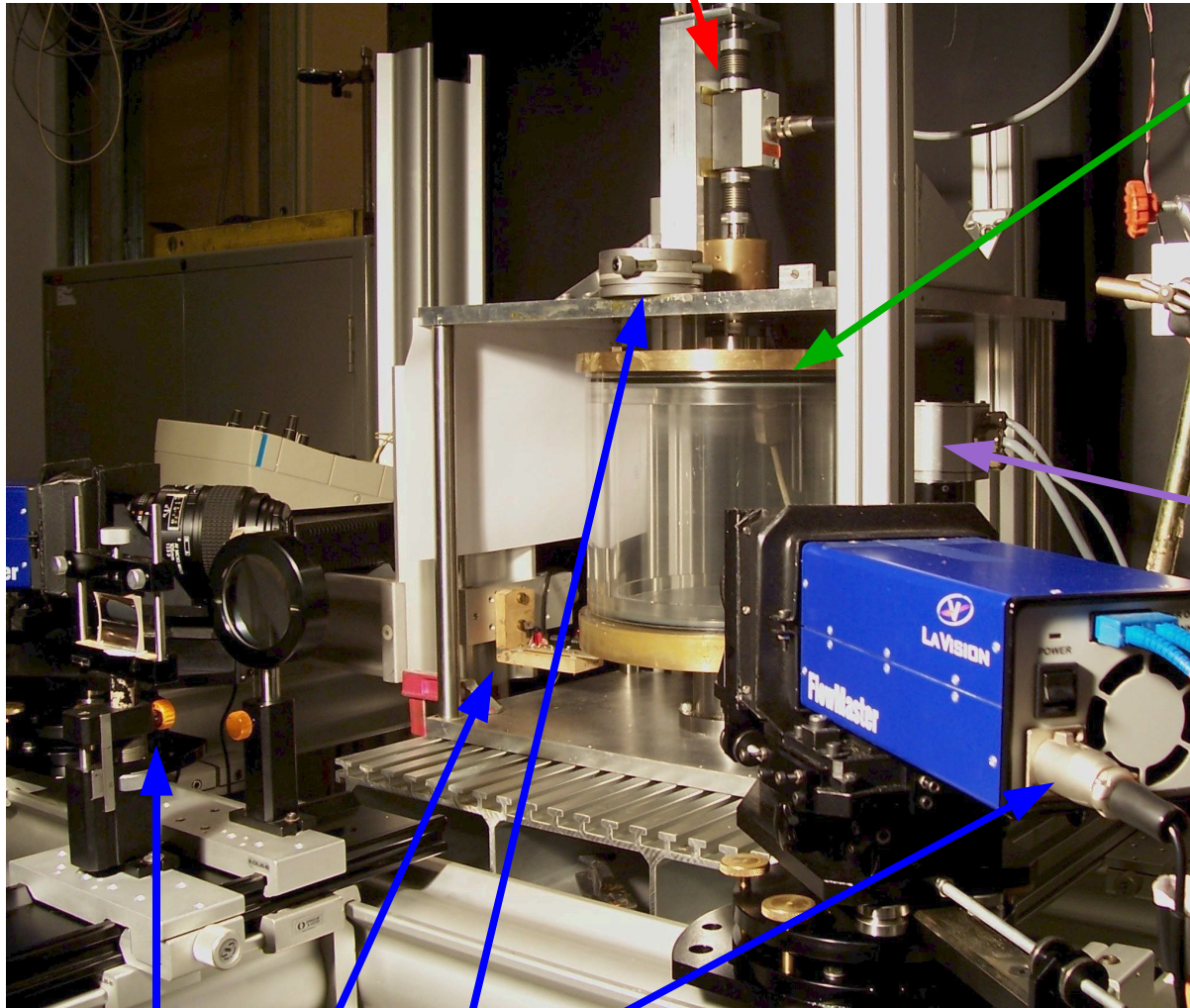
$R_\Omega > 0$ Cyclonic flows (shear and angular velocity have same sign)

$R_\Omega < 0$ Anti-Cyclonic flows

$R_\Omega = 0$ Perfect counterrotation

Taylor-Couette experimental setup

Torque measurements



Two coaxial cylinders

$$R_i = 110 \text{ mm}$$

$$R_o = 120 \text{ mm}$$

$$\text{gap } d = 10 \text{ mm}$$

$$H = 200 \text{ mm}$$

$$\eta = 0,917$$

$$\Gamma = 22$$

Two independent motors:
max speed $f = 10\text{Hz}$

$$R_e = 1,4 \times 10^4 f \text{ for water}$$

Two low-viscous,
refractive index matched fluids :

NaI solution (51%)

Shell Macron oil

(viscosity = 3 x Water)

3C / 2D Velocity measurements
Stereoscopic PIV

Comparison of flow properties for two Rotation numbers

G : Dimensionless torque

(Remind that $G \sim Re$ for viscous flow and that $G \sim Re^2$ for “Kolmogorov turbulence” moreover : $G \sim Re^{1,5}$ for Taylor vortices)

$$G = T / (\rho H v^2)$$

$$G_{lam} = \frac{2 \pi \eta}{(1 - \eta)^2} Re$$

Esser & Grossmann Phys. Fluids 8, 1814 (1996).

Prediction for first instability :

→ $Re^c = 150$ for $R_\Omega = \eta - 1$

$Re^c = 515$ for $R_\Omega = 0$

Here : $Re^c \approx 400$ for $R_\Omega = 0$

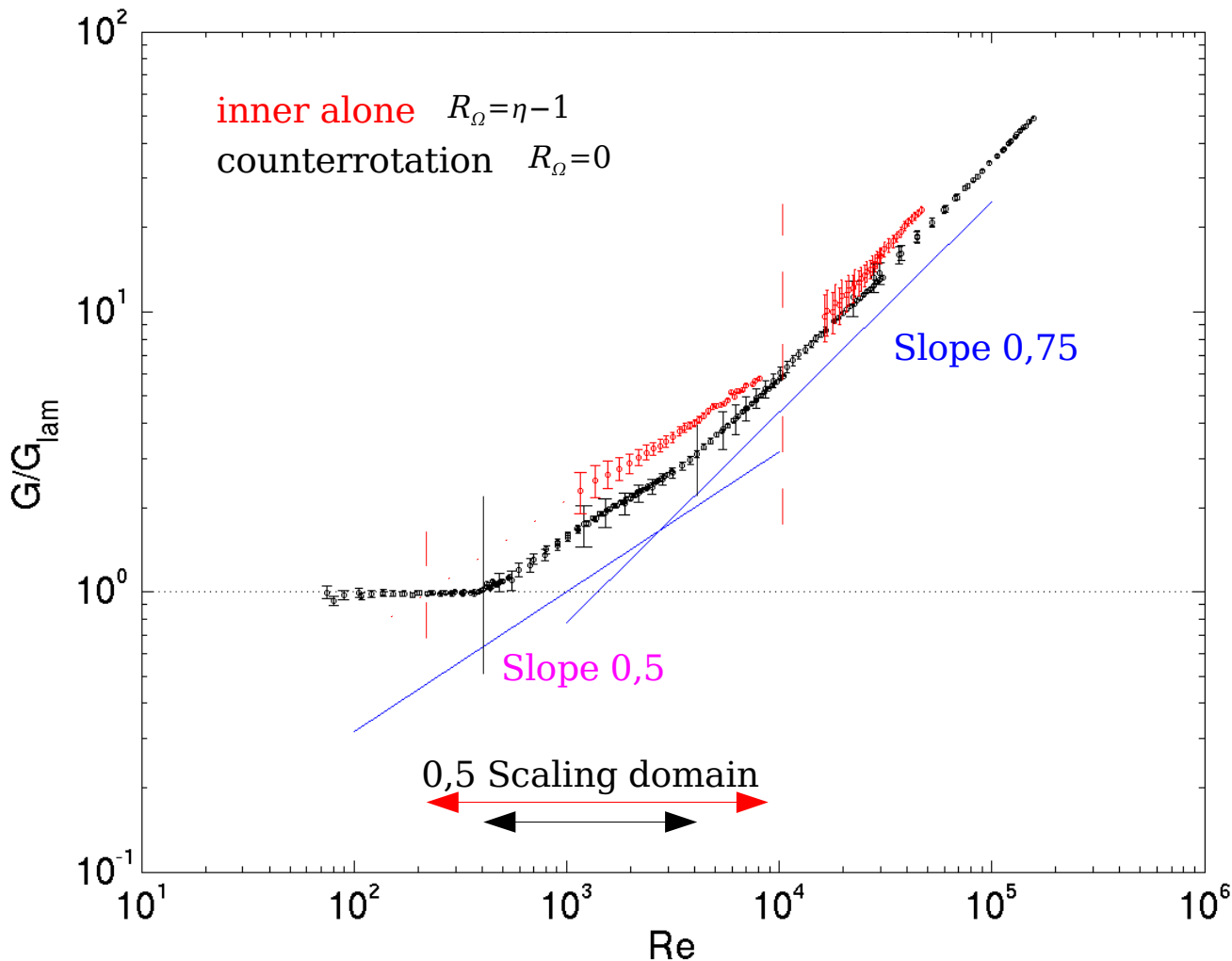
Aspect Ratio ?
Kármán layers ?

The counterrotating flow destabilizes later but develops faster

$G \sim Re^{1,75}$ → “Ultra-hard turbulent regime”

Dubrulle & Hersant EPJB 26, 379 (2002).

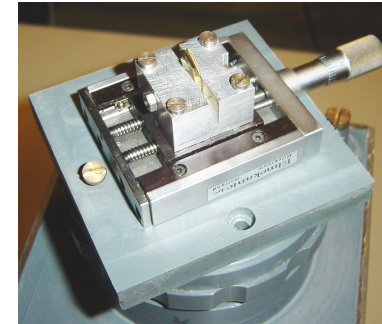
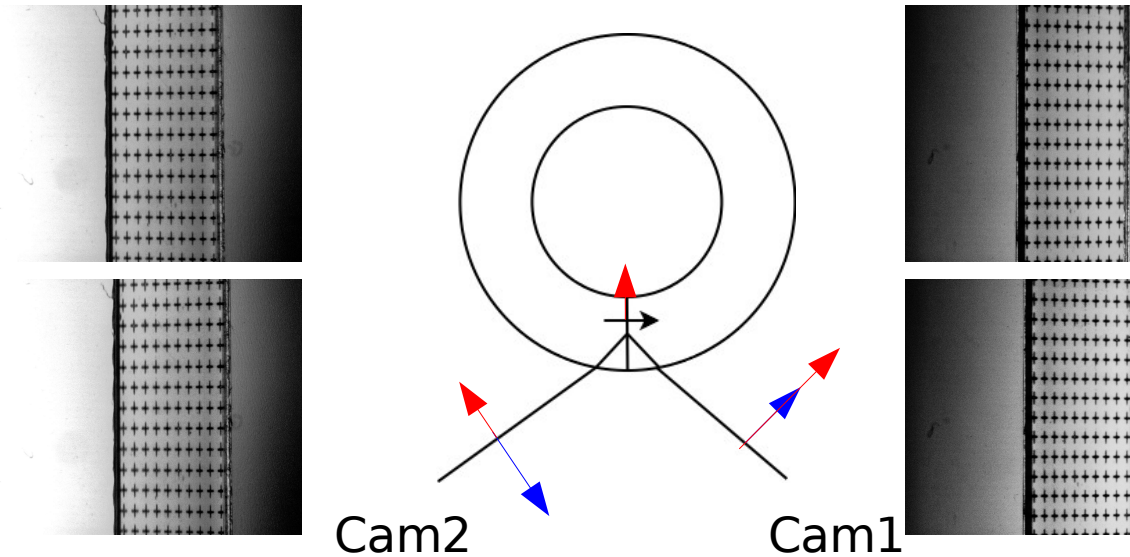
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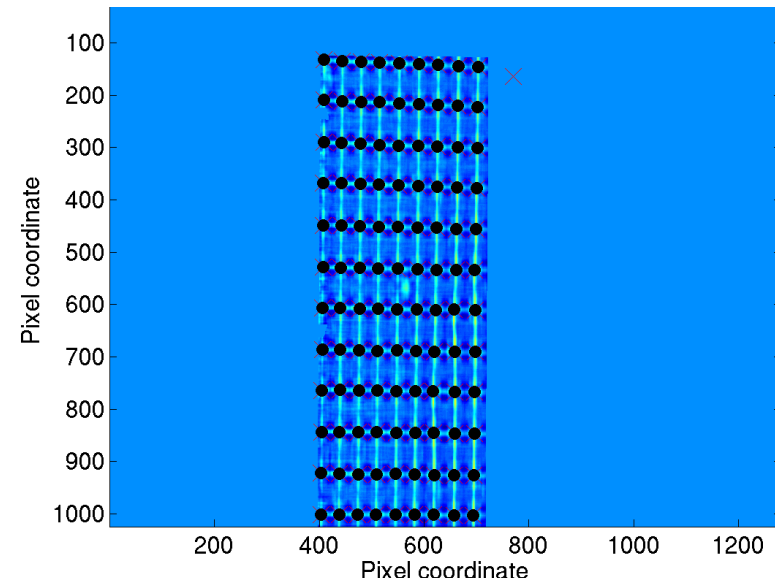
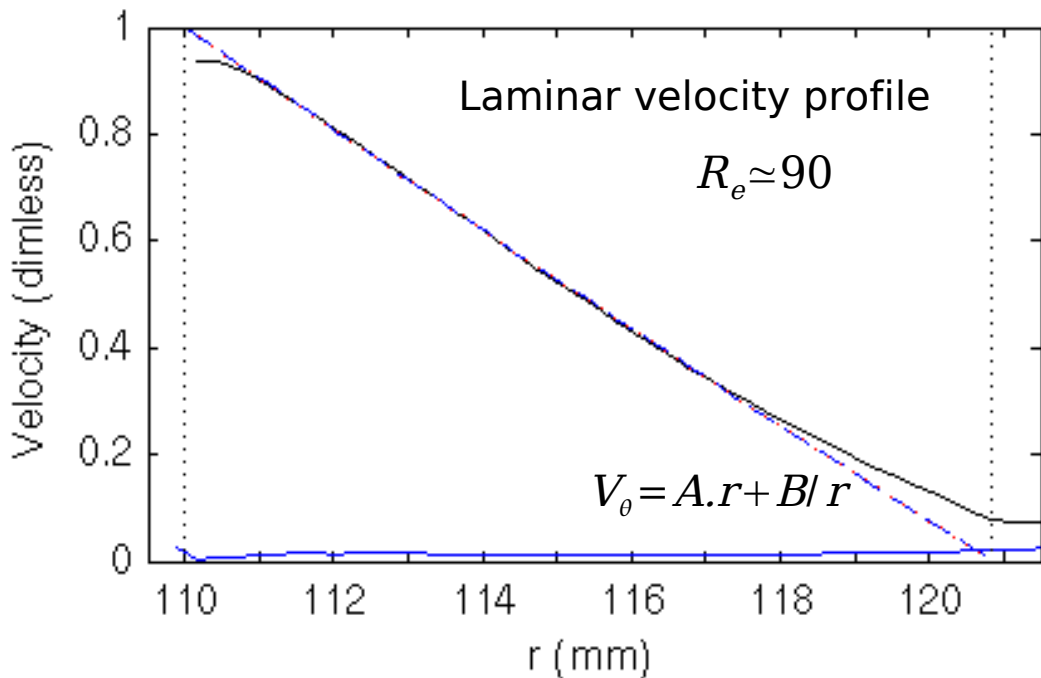
Stereoscopic PIV in single-phase flow

Method which allows measurements of
3 Components in one (2D) plane

Everything relies on the
Calibration procedure



Example of mapping
(each point is a detected cross)
distance between crosses : 1mm



Good measurement, except near the walls

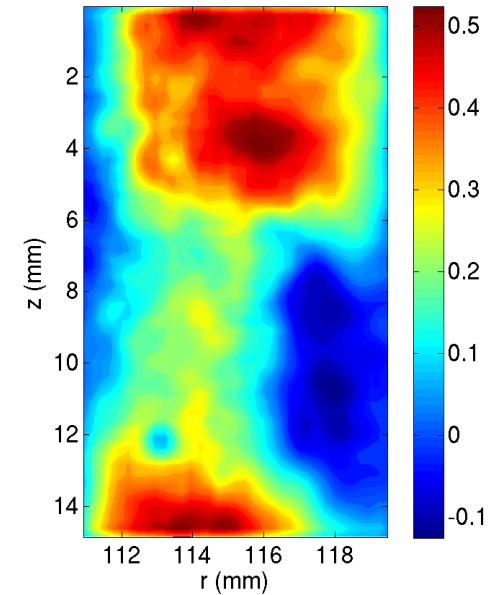
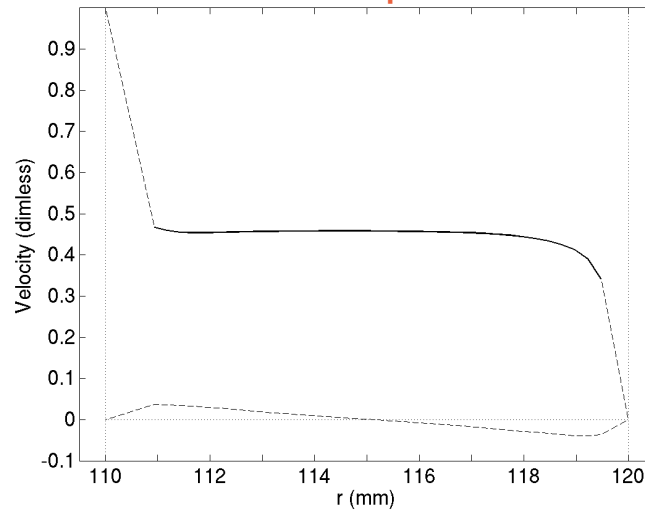
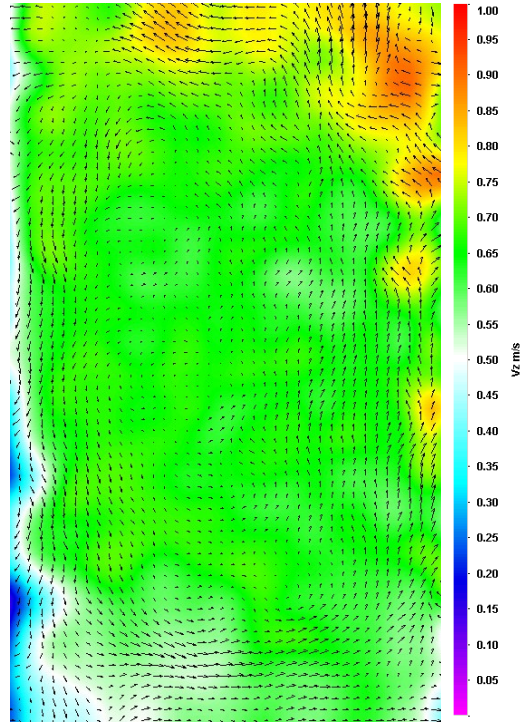
Comparison of velocity fields for two Rotation numbers

Inner Alone flow $R_e \simeq 1,4 \cdot 10^4$

$$R_\Omega = \eta - 1$$

Instantaneous velocity field

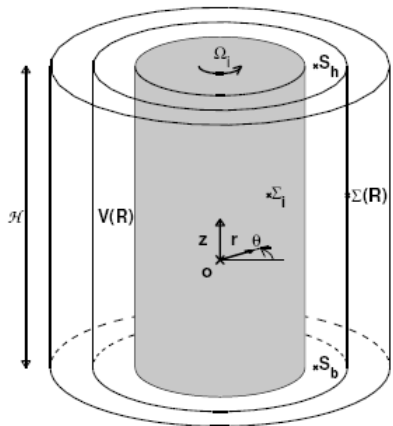
Mean profile



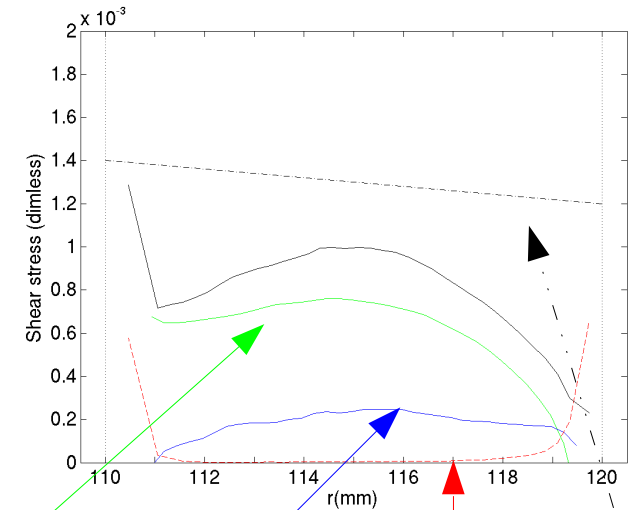
$$\langle V'_\theta V'_r \rangle / (\langle V_\theta^2 \rangle^{1/2} \langle V_r^2 \rangle^{1/2})$$

Taylor Vortices in the time average : main contribution to transport

Angular momentum balance :



- ◆ Inner cylinder gives torque i.e. puts angular momentum into the control volume.
- ◆ The total angular momentum is conserved :
 - ➔ It must exit the control volume through
 - ➔ Viscous diffusion
 - ➔ Advection



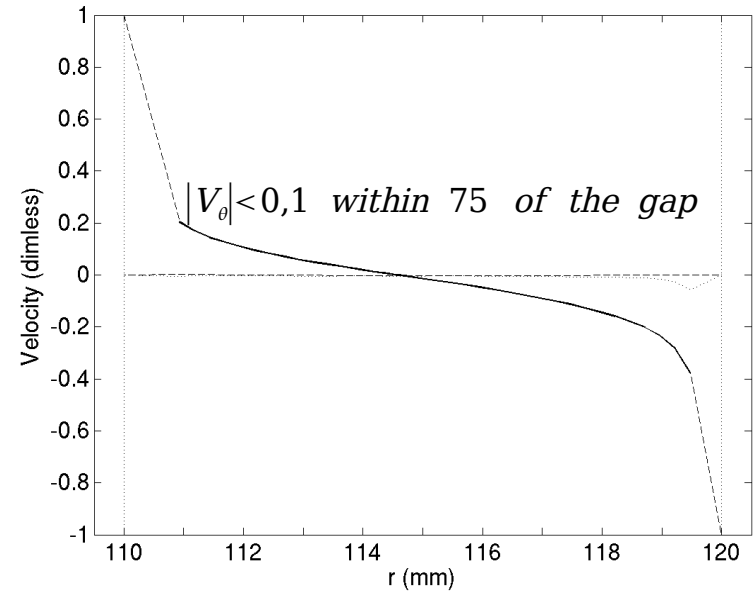
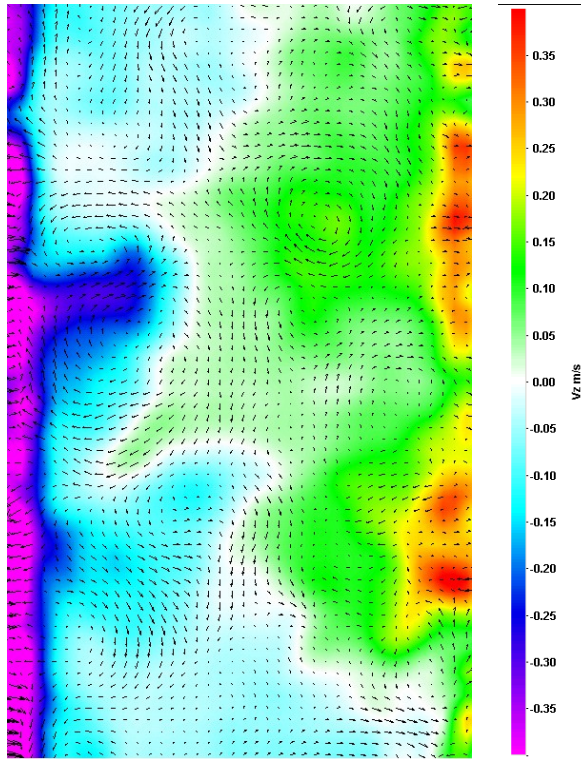
$$\int_{\Sigma} \rho r V_\theta V_r ds + \int_{\Sigma} \rho r \langle v'_\theta v'_r \rangle ds + \mu \int_{\Sigma} r^2 \partial_r \left(\frac{V_\theta}{r} \right) ds = \Gamma$$

Small fluctuations $v'_\theta \simeq 0,03$ $v'_r = v'_z \simeq 0,02$

Comparison of velocity fields for two Rotation numbers

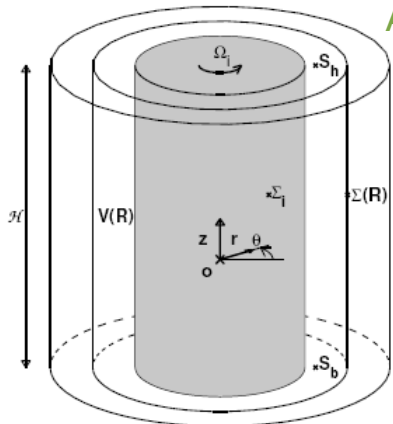
Counterrotating turbulent flow $Re \simeq 1,4 \cdot 10^4$

Instantaneous velocity field
Mean profile

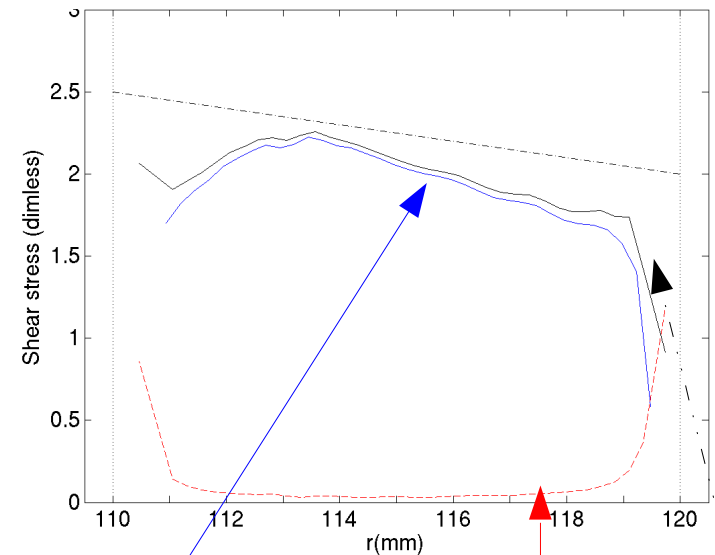


No z-dependance :
Turbulent stress dominates

Angular momentum balance :



- ◆ Inner cylinder gives torque
i.e. puts angular momentum into the control volume.
- ◆ The total angular momentum is conserved :
→ It must exit the control volume through → Viscous diffusion
→ Advection



$$\int_{\Sigma} \rho r V_{\theta} V_r ds + \int_{\Sigma} \rho r \langle v'_{\theta} v'_r \rangle ds + \mu \int_{\Sigma} r^2 \partial_r \left(\frac{V_{\theta}}{r} \right) ds = \Gamma$$

Anisotropy $v_{\theta}' \simeq 0,1$ $v_r' = v_z' \simeq 0,05$

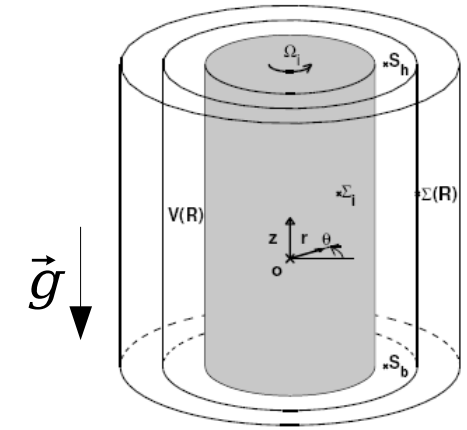
Cross-correlation: 0,4

Qualitative picture of dispersion process

Refractive index matching

Fluids :

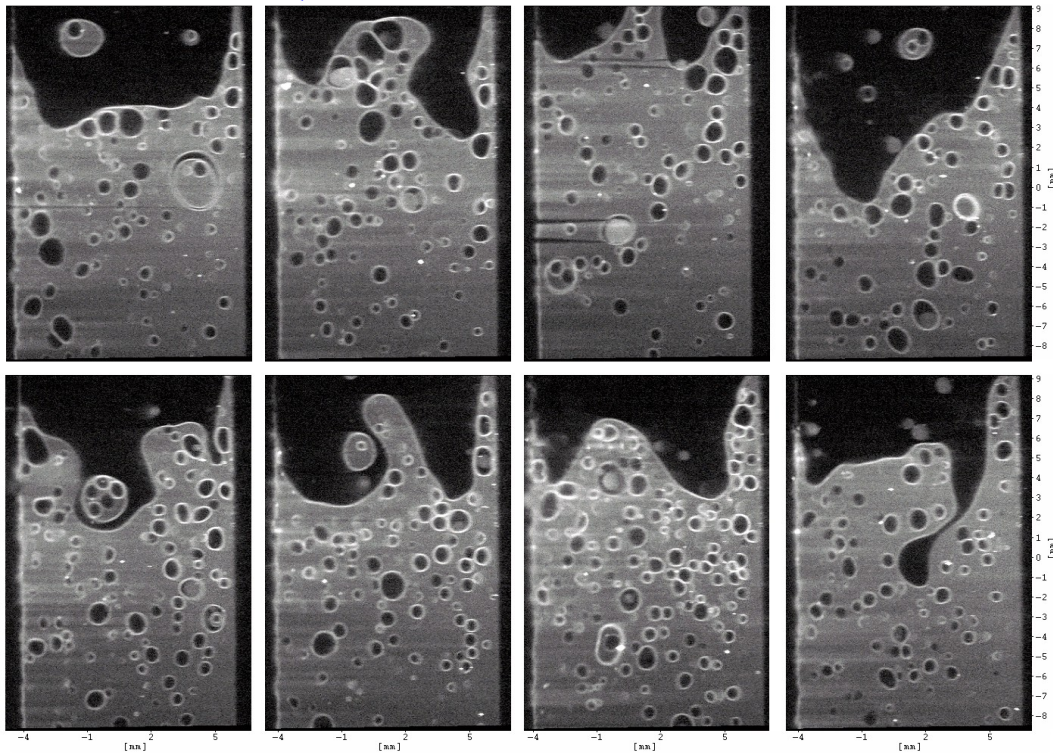
- ◆ Water $\rho=1000 \quad \mu=10^{-3} \quad \nu=10^{-6} \quad R.I.=1,331$
- ◆ Glycerol 86% $\rho=1230 \quad \mu=0,126 \quad \nu=10^{-4} \quad R.I.=1,450$
- ◆ Glycerol 75% $\rho=1190 \quad \mu=0,036 \quad \nu=3,0 \cdot 10^{-5} \quad R.I.=1,434$
- ◆ Shell Macron 110 Oil $\rho=800 \quad \mu=2,7 \cdot 10^{-3} \quad \nu=3,4 \cdot 10^{-6} \quad R.I.=1,445$
- ◆ NaI solution $\rho=1550 \quad \mu=2 \cdot 10^{-3} \quad \nu=1,3 \cdot 10^{-6} \quad R.I.=1,445$



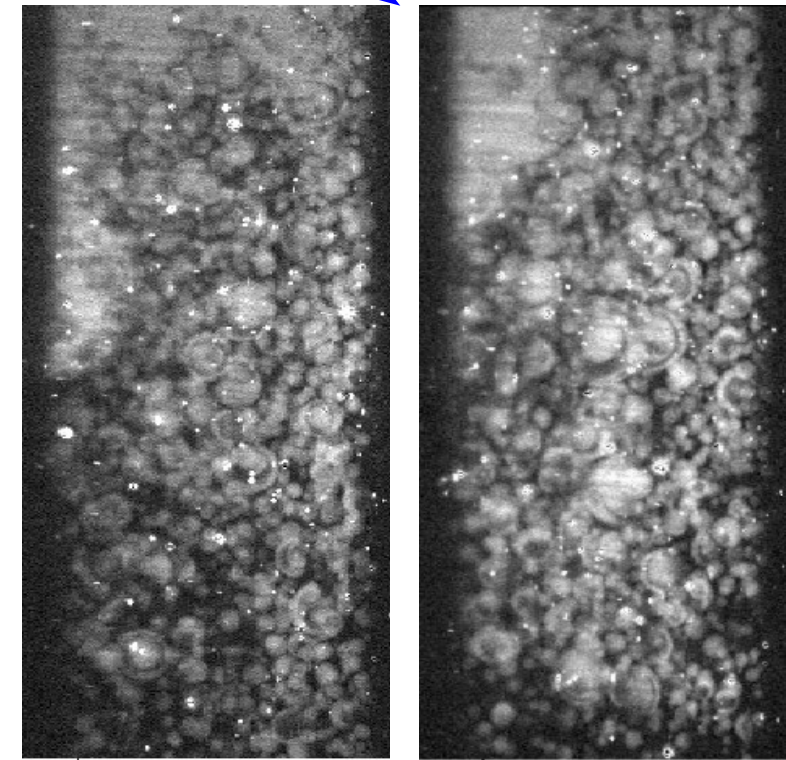
At rest : two layers

Counterrotating at 2Hz : dispersion starts

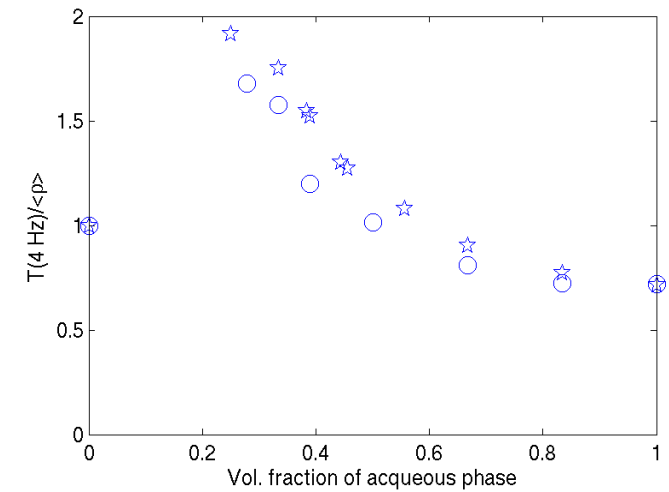
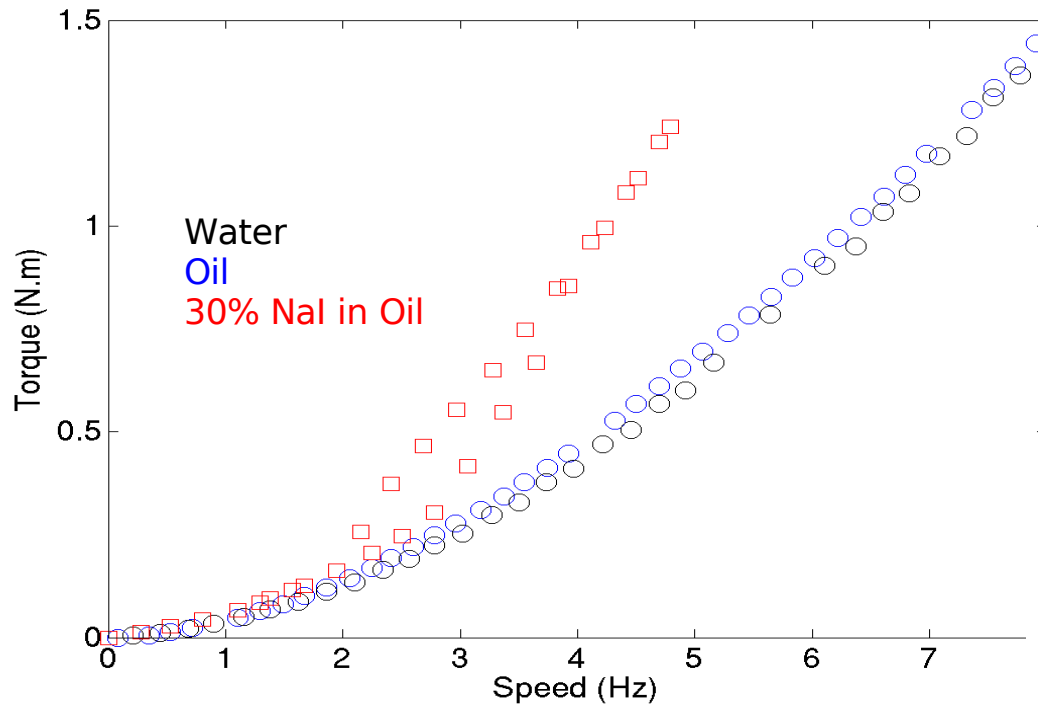
30% NaI in Oil



Counterrotating at 3Hz : concentrated dispersion



Quantitative measurements : Evolution of the torque



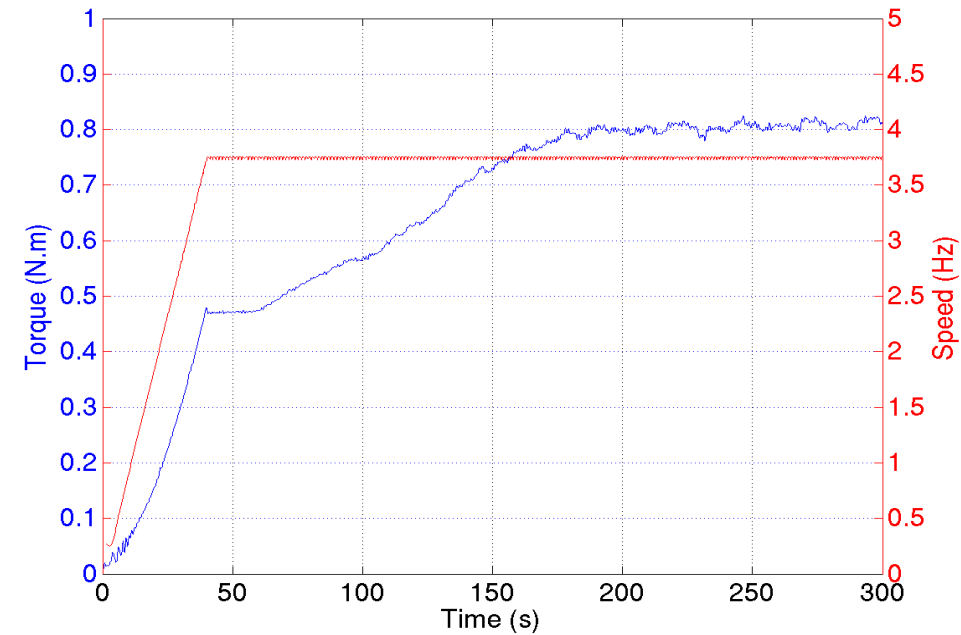
Relevant
parameters :

Froude number ?

$$\sqrt{\frac{\rho u_x^2}{\Delta \rho g d}} = 0.23f$$

Weber number ?

$$\frac{\rho u_x^2 d}{\sigma} = 0.6 f^2$$



Conclusions & Perspectives

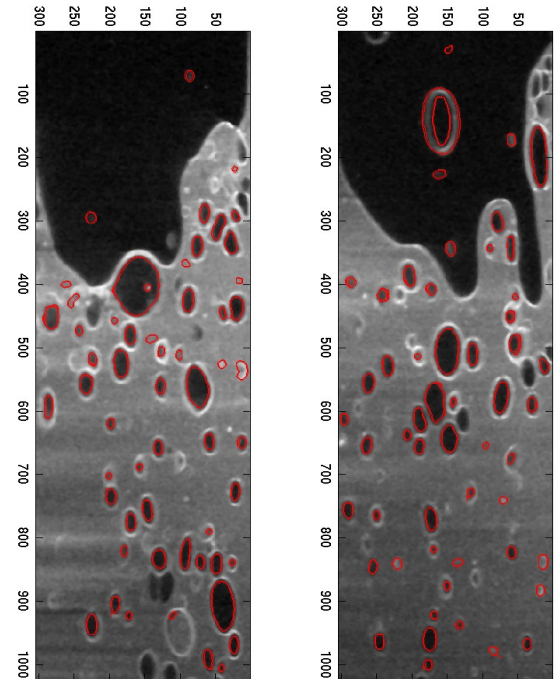
- Torque measurements now reliable, reveal interesting physics.

Subcritical transition to turbulence.

$$R_\Omega < -1 \quad ; \quad R_\Omega > 1/\eta - 1$$

- Stereoscopic PIV : torque scaling, subcritical regimes ?

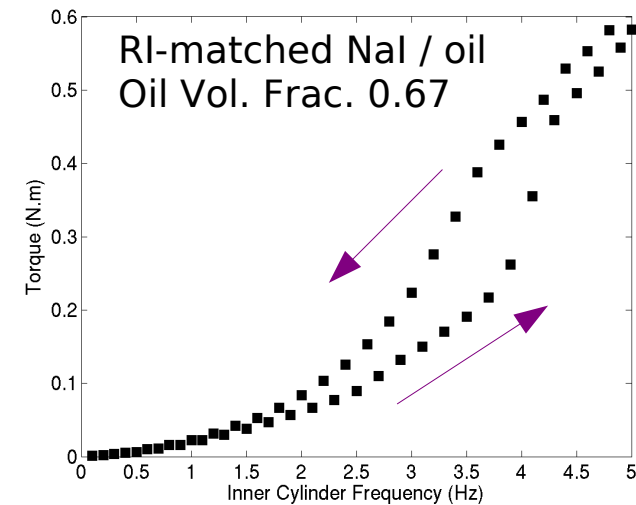
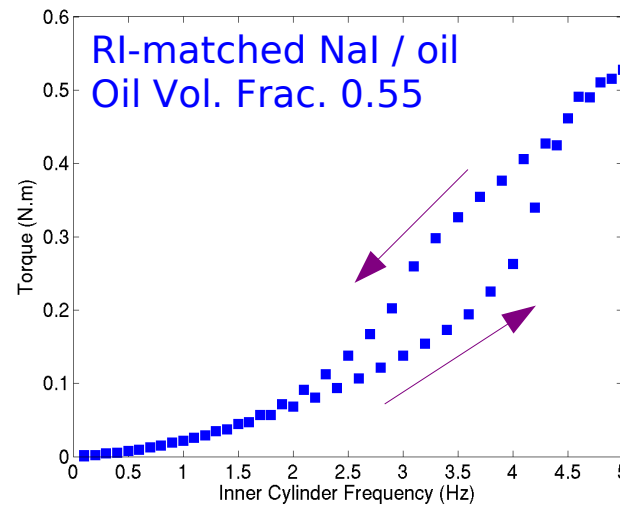
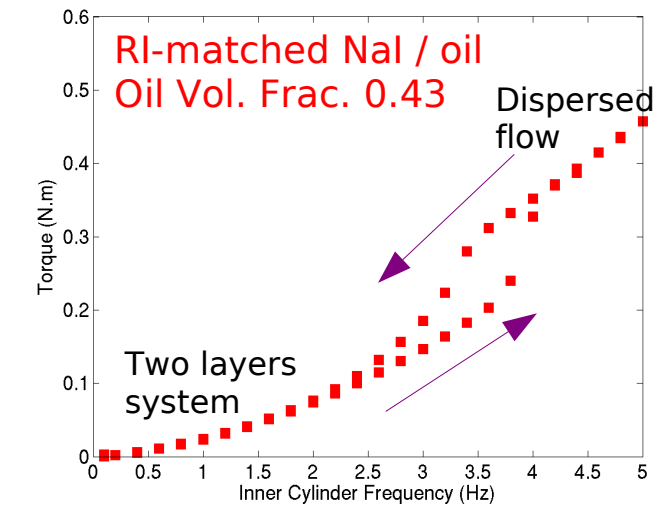
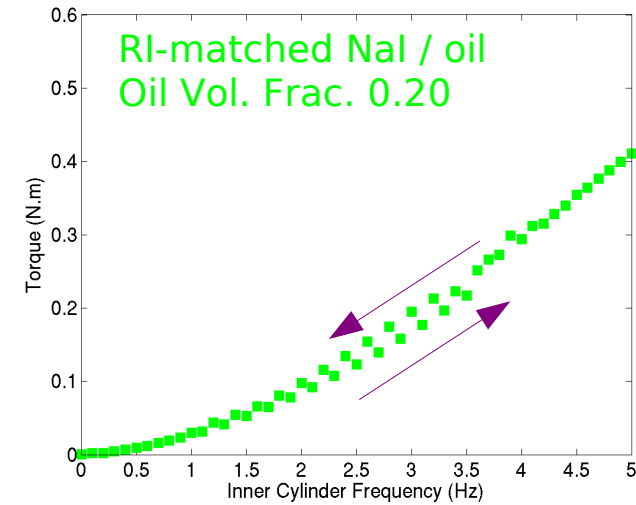
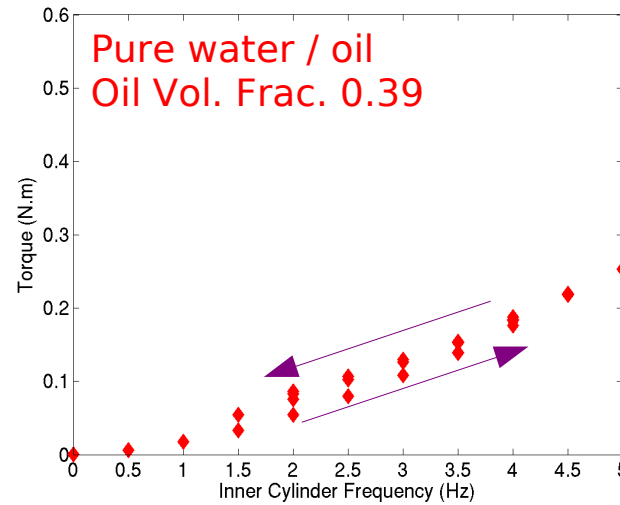
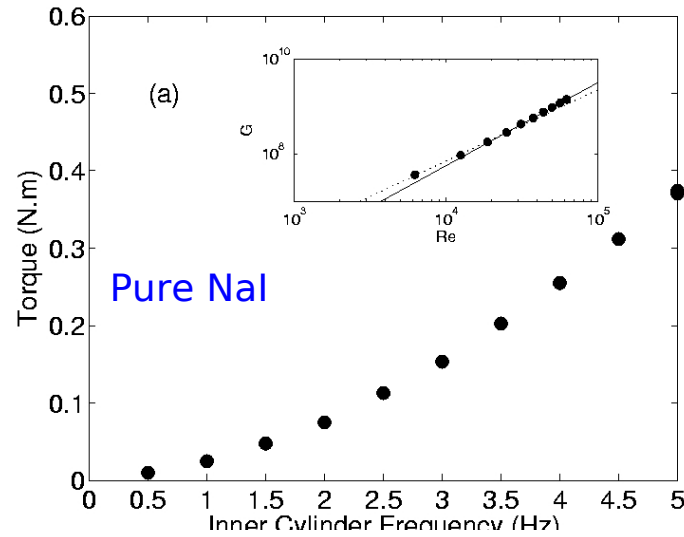
- Two-phase flow : Effective viscosity,
Droplets distribution.
Long time behaviour ?



Torque measurements in a pre-experiment

(Counterrotating TCF, $R_i=100$ mm $R_o=110$ mm, no optical access)

Back and Forth increase of the parameter control,
Measurement time: 30 s



Torques reveal the onset of turbulent dispersion.
Seems to depend on volume fraction.
Hysteresis loop : time variations

Long time behaviour

Starting from one speed, the system is suddenly set to another one.

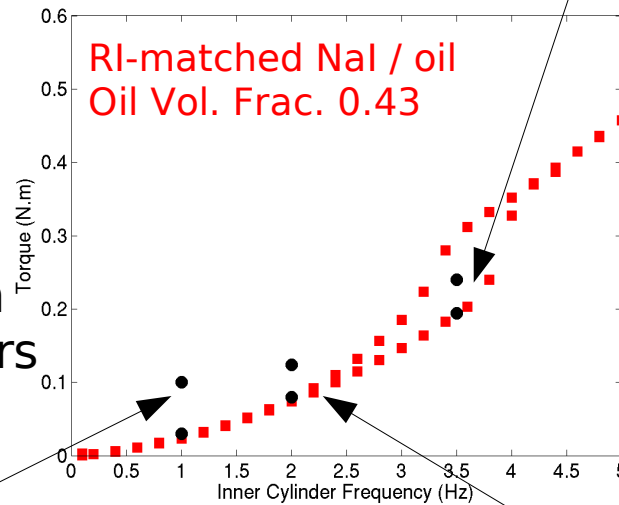
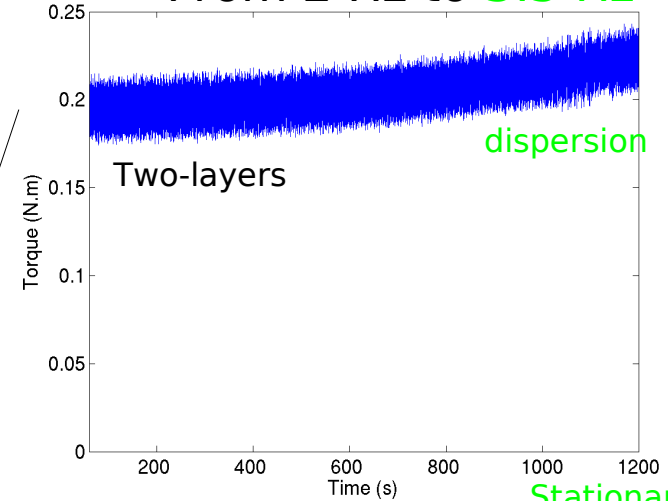
Very slow process

Study of decaying time will help to define a threshold for dispersion



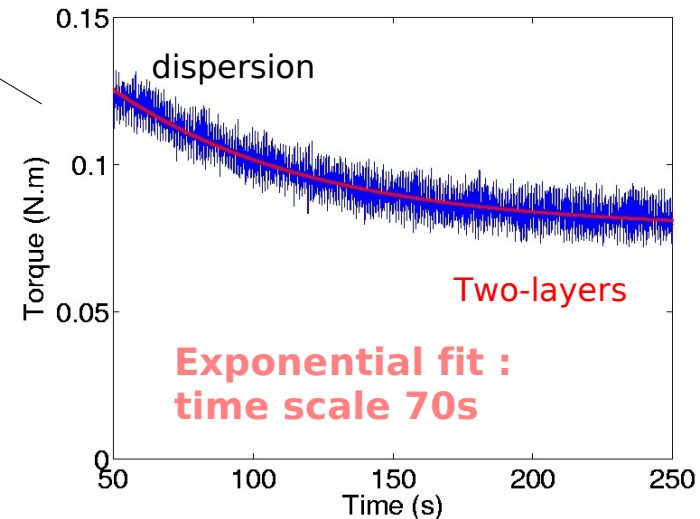
For this vol. fraction:
< 2Hz : unstable dispersion
> 3.5Hz : unstable two-layers

From 2 Hz to 3.5 Hz



Two different times

From 3.5 Hz to 2 Hz



From 5 Hz to 1 Hz

