

Emergence of large scale secondary flow in a turbulent Taylor-Couette flow.

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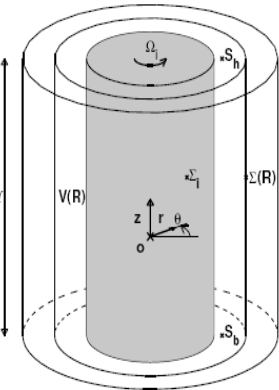


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Taylor-Couette flow background

Coaxial rotating cylinders



Geometry

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

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

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

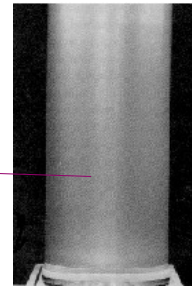
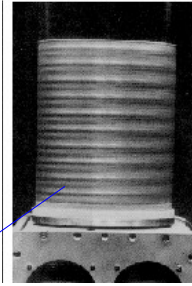
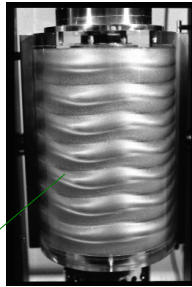
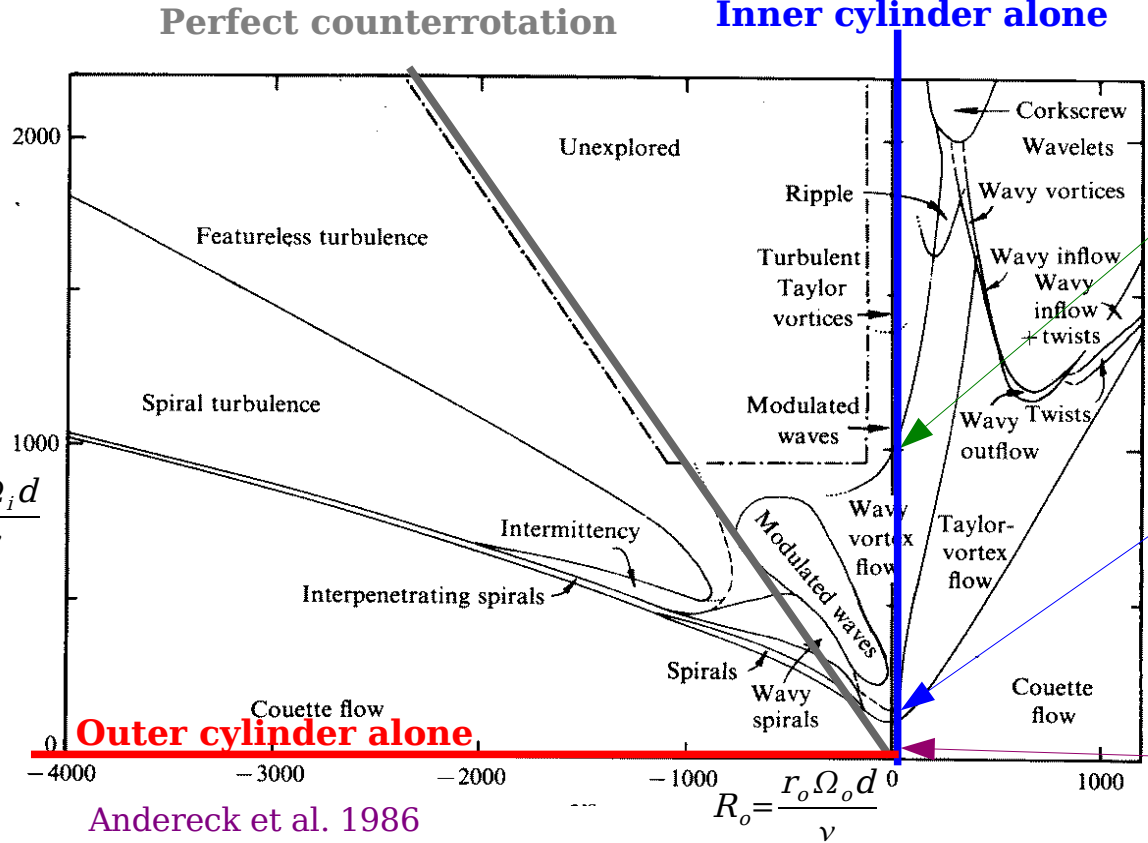
$$R_i = \frac{r_i \Omega_i d}{\nu}$$

Kinematic parameters

Ω_i Inner cylinder ang. velocity

Ω_o Outer cylinder ang. velocity

ν Kin. viscosity



◆ Low Re : visualization technique study of instabilities

◆ High Re : study of torque scaling

Andereck et al. 1986
Prigent & Dauchot, 2000
Esser & Grossmann, 1996
Lathrop et al. 1992
Dubrulle & Hesrant, 2002
Eckhardt et al. 2006

Dynamics motivated choice of parameters

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

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

$R_\Omega < 0$ Anti-Cyclonic flows

$R_\Omega = 0$ Perfect counterrotation

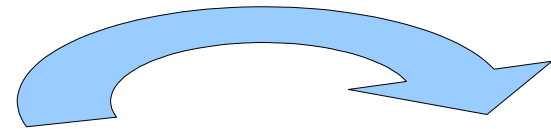
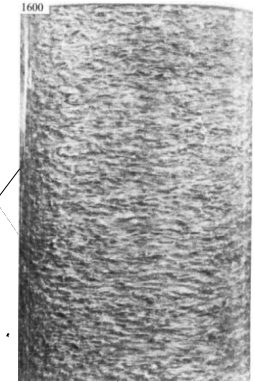
Rotation number : $R_\Omega = (1-\eta) \frac{R_i + R_o}{\eta R_o + R_i}$

Pattern formation in turbulent flows

Inner cylinder alone :
structures still present at high Re $R_e > 10^4$

He & Tanahashi, 11th Eur. Turb Conf, Porto, 2007
Bilson & Bremhorst, JFM 579, 227, 2007

Outer cylinder alone is linearly stable,
but turbulent at high Re,
without any large-scale features.



How do you go from
one situation to the other ?

Inner cylinder alone

Counterrotation

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

Featureless
turbulence

Unexplored

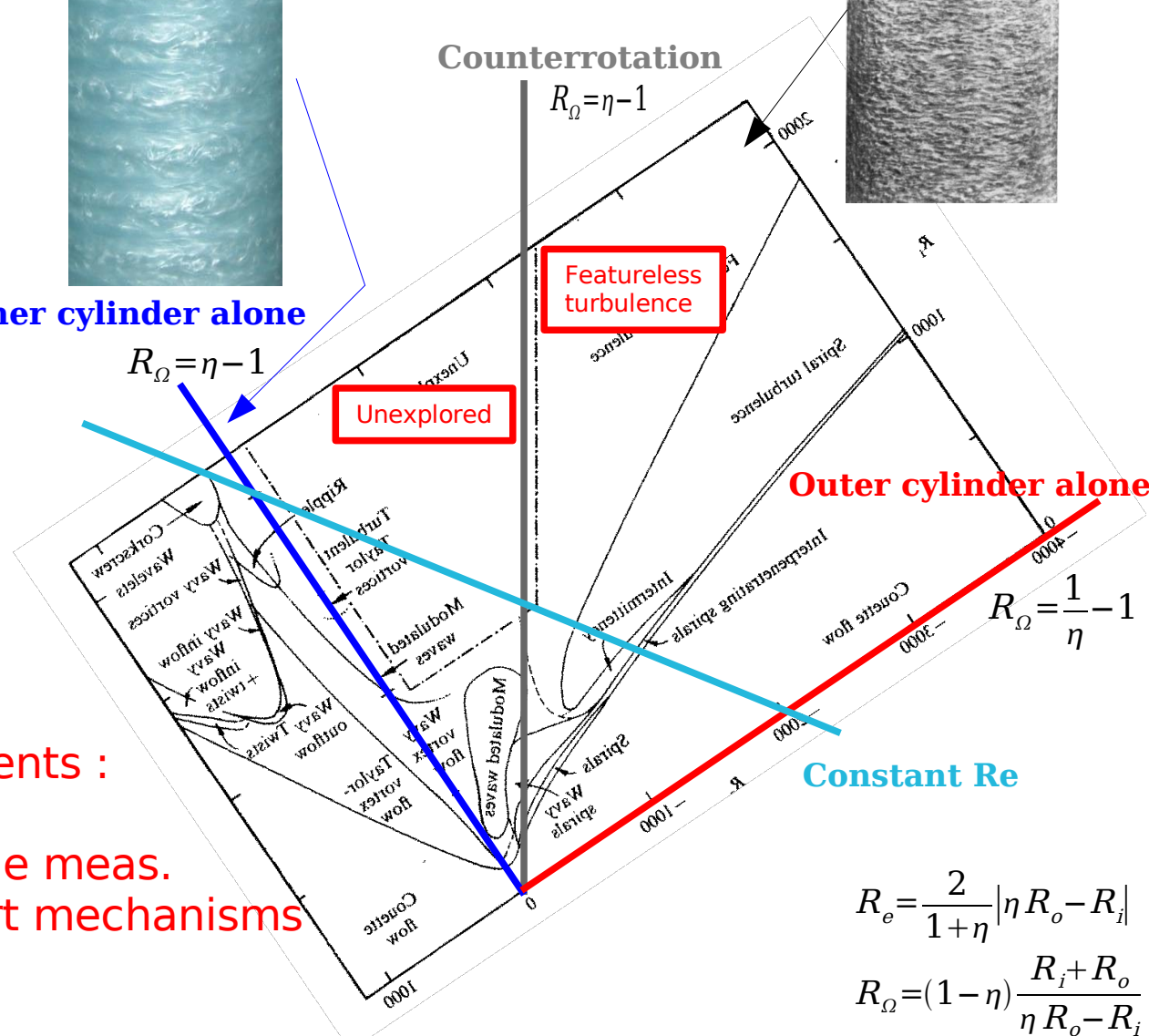
Outer cylinder alone

$$R_\Omega = \frac{1}{\eta} - 1$$

Constant Re

We developed an experiment,
with 3C-PIV and torque measurements :

quantitative velocity and torque meas.
qualitative pictures of transport mechanisms



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

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

Taylor-Couette experimental setup

Torque measurements

Two coaxial cylinders

$$\begin{aligned} R_i &= 110 \text{ mm} \\ R_o &= 120 \text{ mm} \\ \text{gap } d &= 10 \text{ mm} \\ H &= 220 \text{ mm} \end{aligned}$$

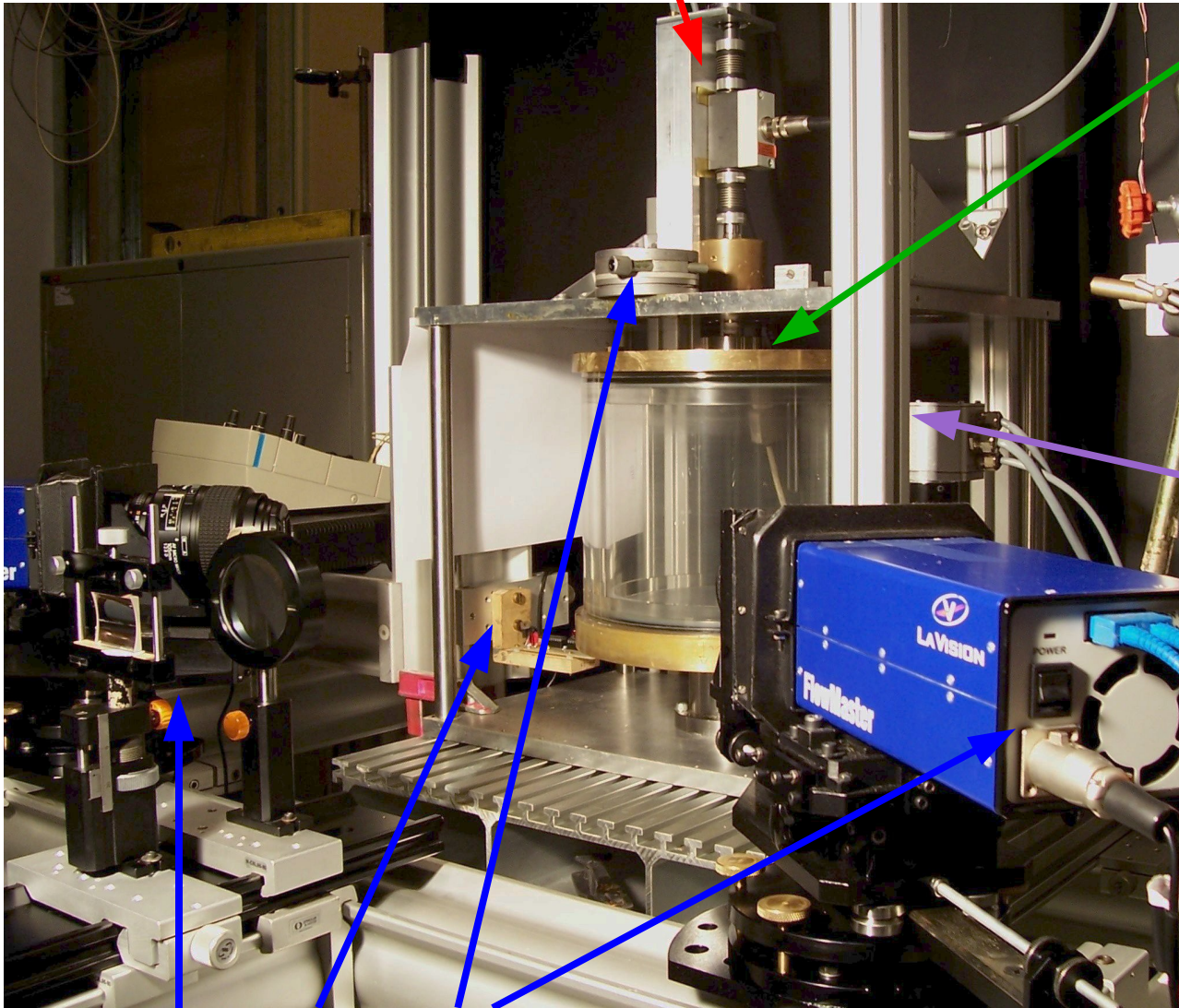
$$\begin{aligned} \eta &= 0,917 \\ \Gamma &= 22 \end{aligned}$$

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

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

Various glycerol/water mixtures

$$\text{viscosity} : 1 \times 10^{-3} \text{ Pa}\cdot\text{s} < \mu < 1 \text{ Pa}\cdot\text{s}$$

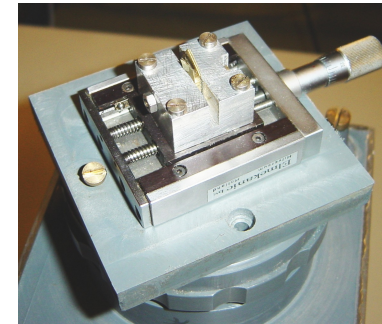
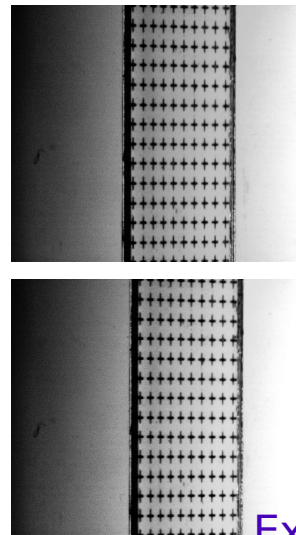
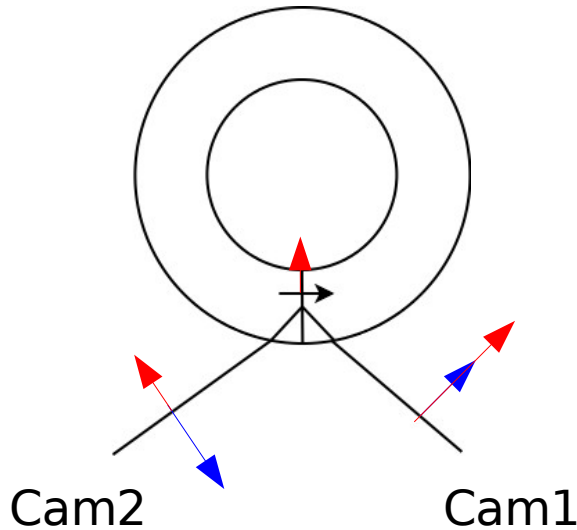
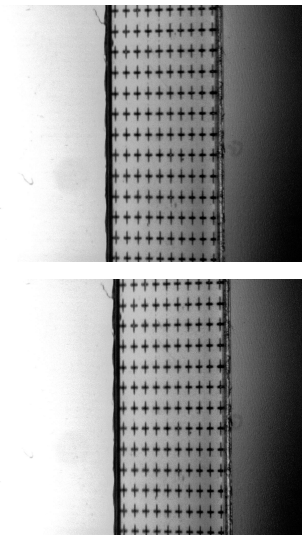


3C / 2D Velocity measurements
Stereoscopic PIV

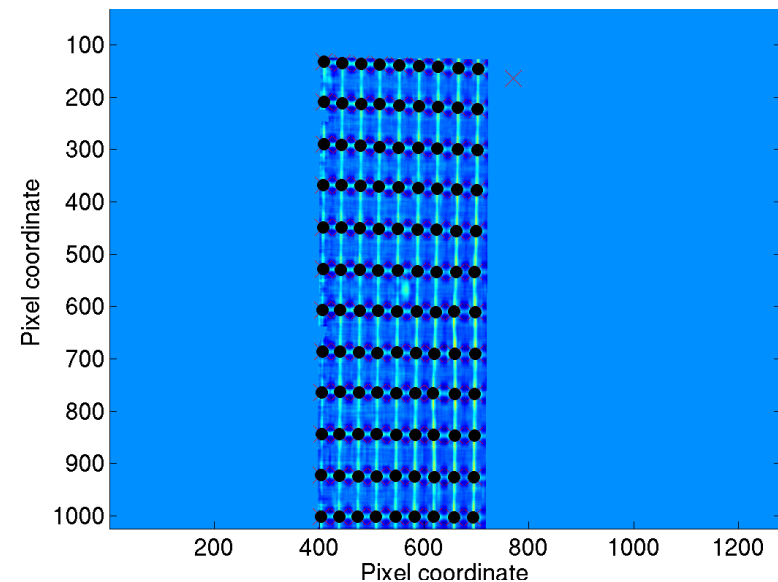
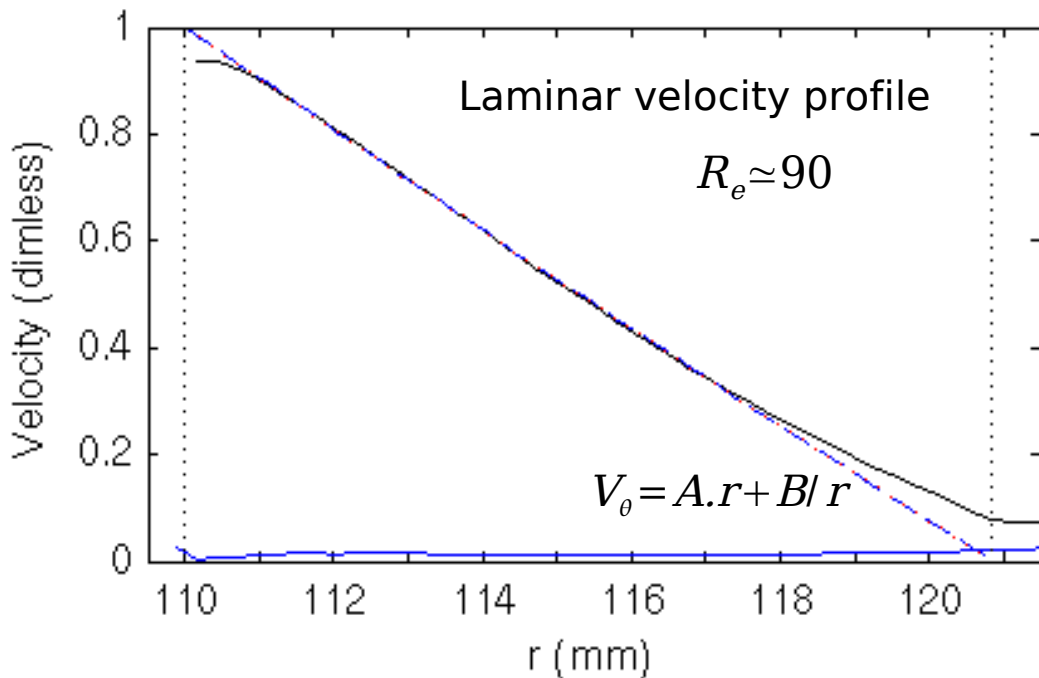
Stereoscopic PIV in single-phase flow

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

Everything relies on the
Calibration procedure

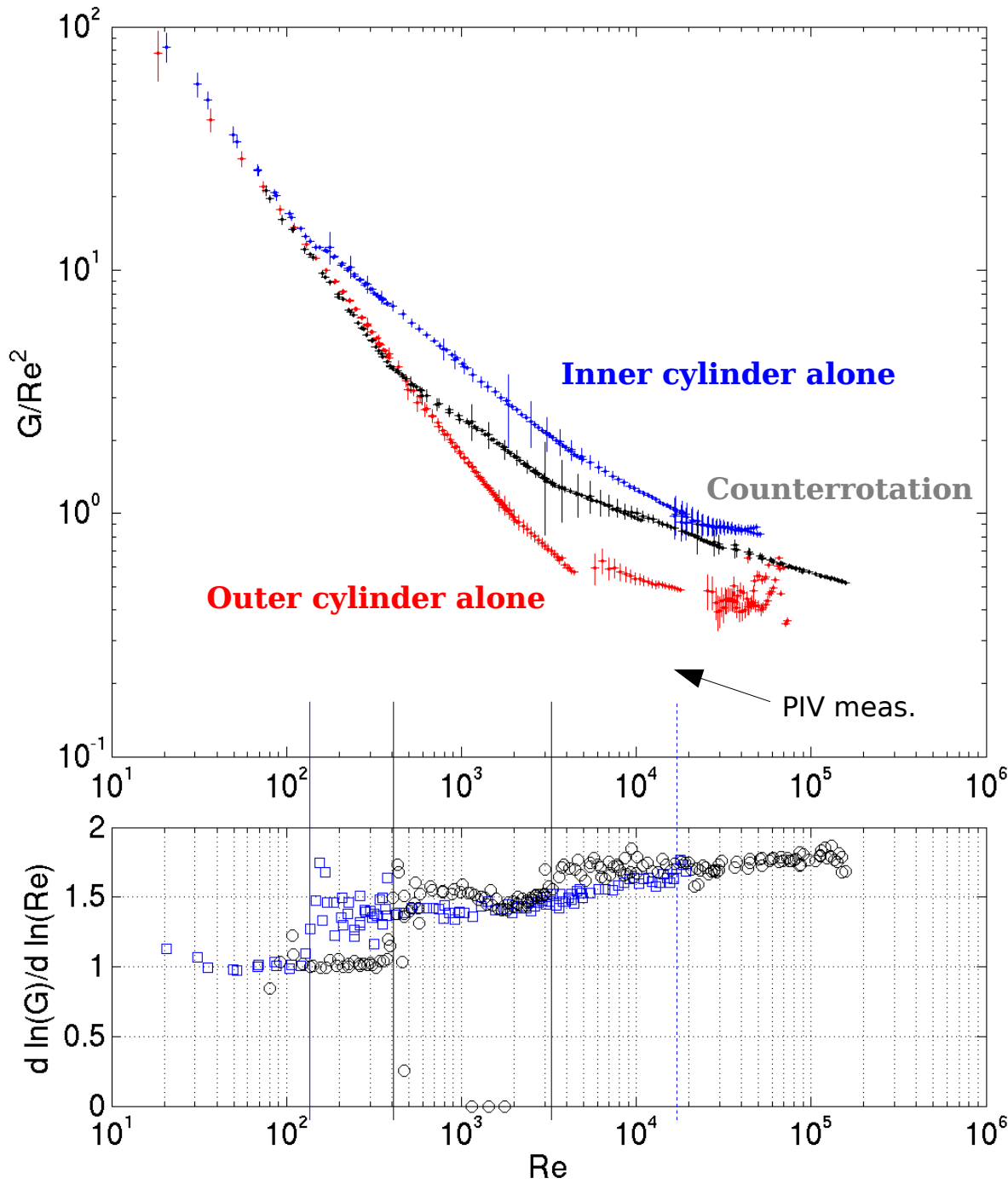


Example of mapping
(each point is a detected cross)
distance between crosses : 1mm



Good measurement, except near the walls

Non-dimensional torque scaling for 3 different rotation numbers



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

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

$G \sim Re$ for viscous flow

$G \sim Re^2$ for "Kolmogorov turbulence"

$G \sim Re^{1.5}$ for Taylor vortices

$G \sim Re^{1.75}$ \rightarrow "Ultra-hard turbulent regime"

Dubrulle & Hersant EPJB 26, 379 (2002).

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

Prediction for first instability :

$$\begin{aligned} \rightarrow R_e^c &= 150 & \text{for } R_\Omega &= \eta - 1 \\ R_e^c &= 515 & \text{for } R_\Omega &= 0 \end{aligned}$$

$$\begin{aligned} \text{Here : } R_e^c &\approx 140 & \text{for } R_\Omega &= \eta - 1 \\ R_e^c &\approx 400 & \text{for } R_\Omega &= 0 \end{aligned}$$

Finite Aspect Ratio, end effects ?

◆ Above $Re \approx 10^4$ all three seem "turbulent".

◆ Counter shows second transition

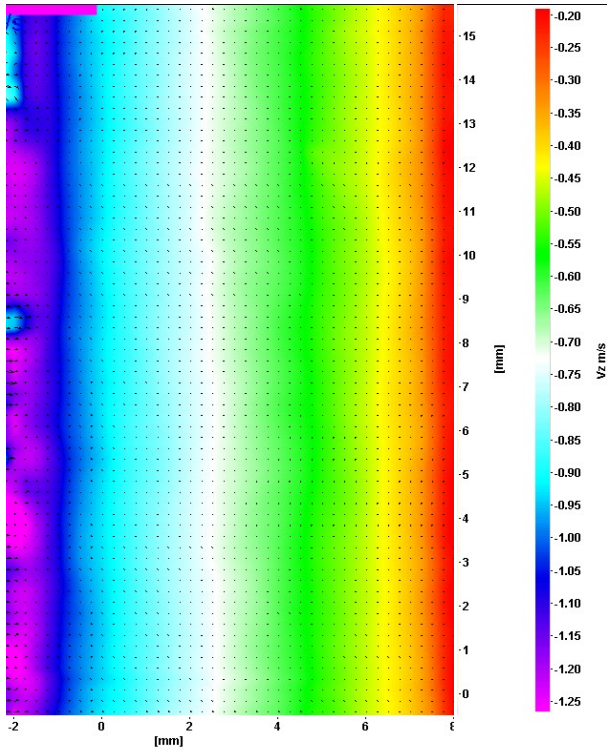
◆ Hierarchy of torques :
Inner > Counter > Outer

Comparison of velocity fields for three Rotation numbers

Outer Alone

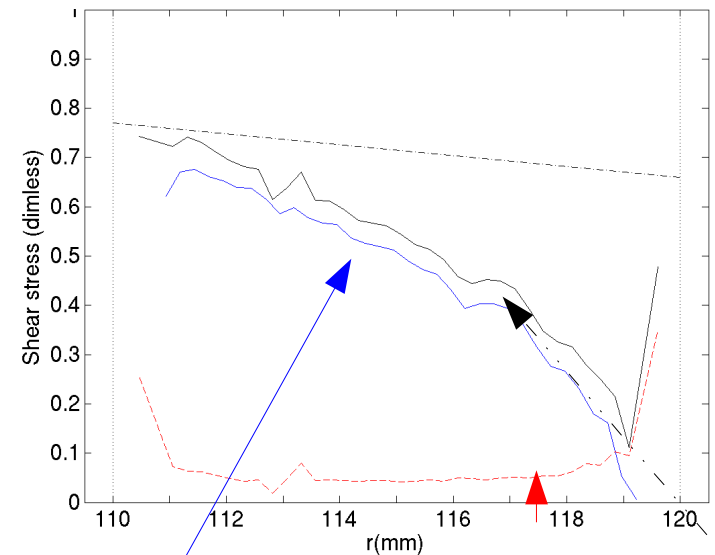
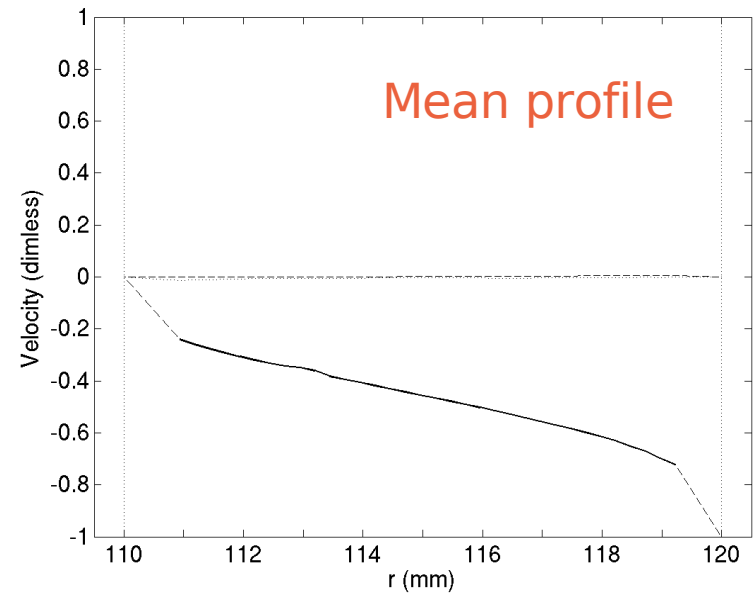
$$R_e \simeq 1,4 \cdot 10^4$$

Mean velocity field



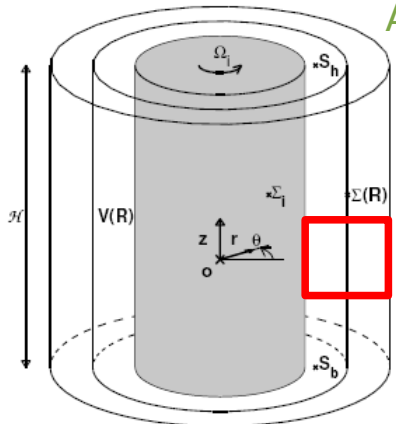
No z-dependance,
No secondary flow,

Turbulent stress
dominates but
Viscous stress still
contribute to 10%
of transport.



Angular momentum balance :

- ◆ One 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

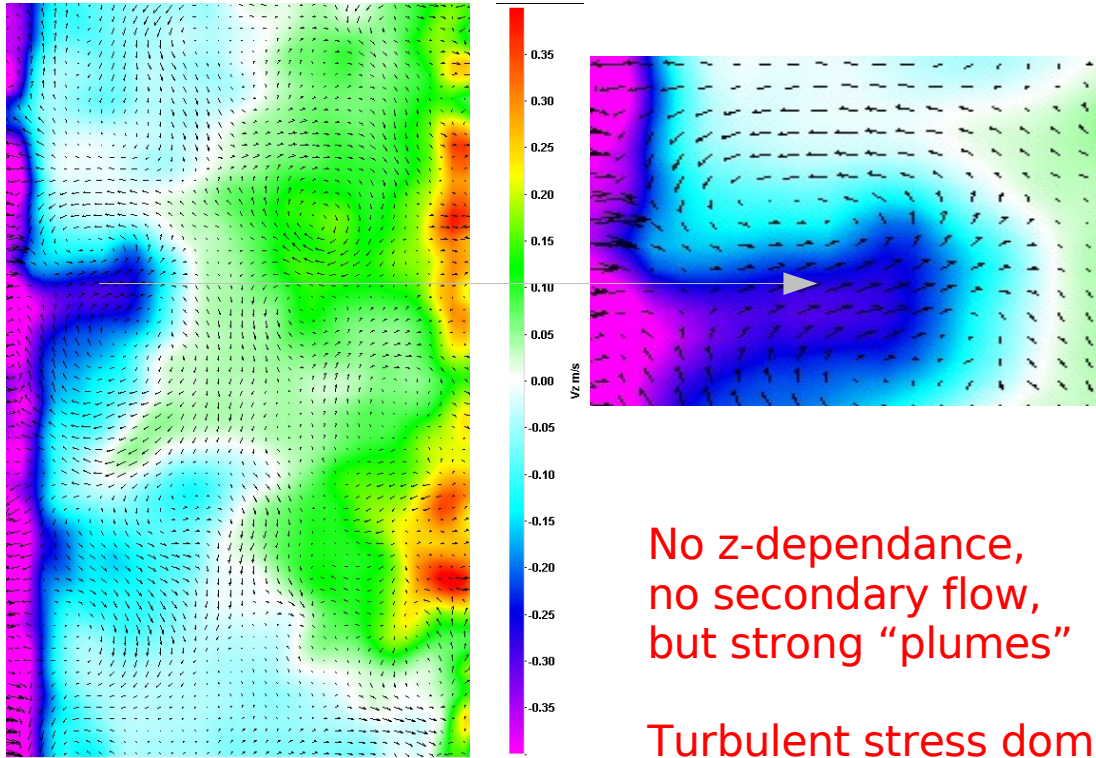


$$\int_{\Sigma} \rho r V_{\theta} V_r ds + \int_{\Sigma} \rho r \langle v'_{\theta} v'_r \rangle ds + \mu \int_{\Sigma} r^2 \partial_r \left(\frac{V_{\theta}}{r} \right) ds = \Gamma$$

Comparison of velocity fields for three Rotation numbers

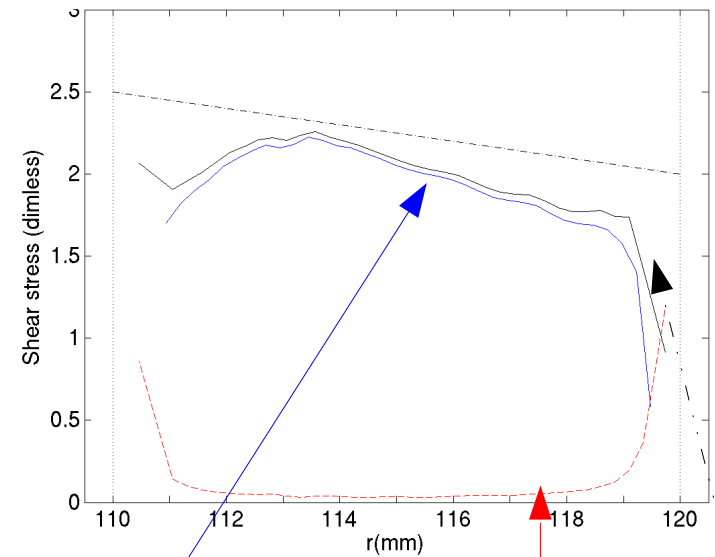
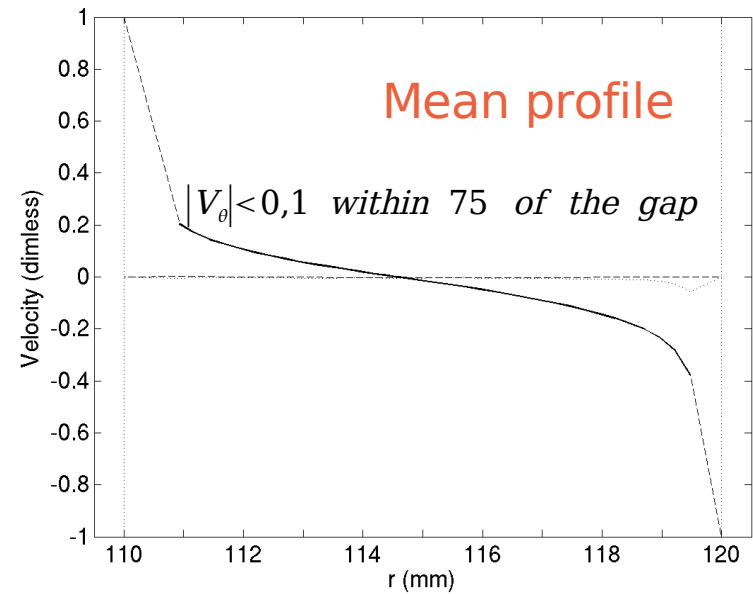
Counterrotating turbulent flow $R_e \approx 1,4 \cdot 10^4$

Instantaneous velocity field



No z-dependance,
no secondary flow,
but strong "plumes"

Turbulent stress dominates



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

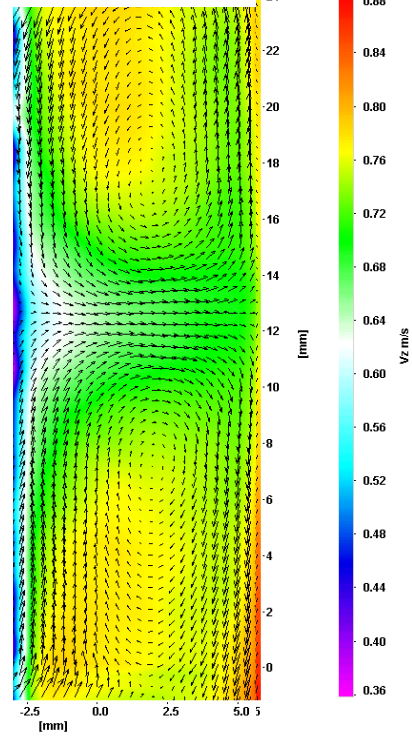
Anisotropy of fluctuations: $v'_{\theta} \approx 0,1$ $v'_r = v'_z \approx 0,05$

Cross-correlation of radial and azimuthal fluctuations: 0,4

Comparison of velocity fields for three Rotation numbers

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

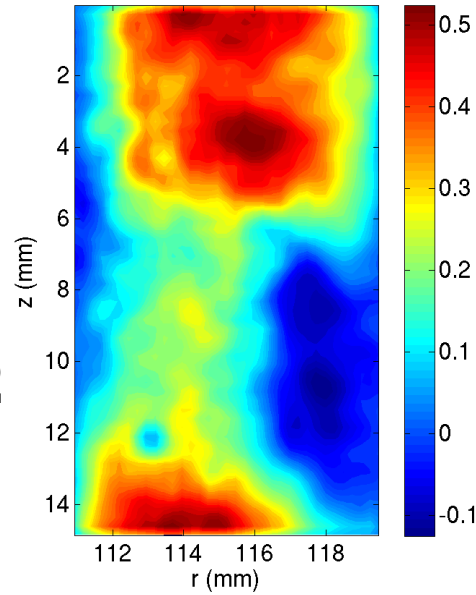
$$R_\Omega = \eta - 1$$



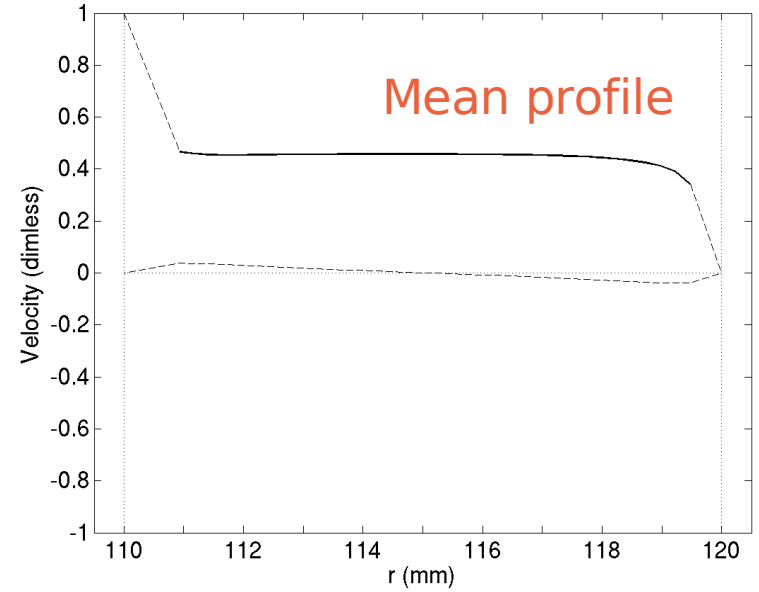
Mean velocity field

Strong secondary flow:

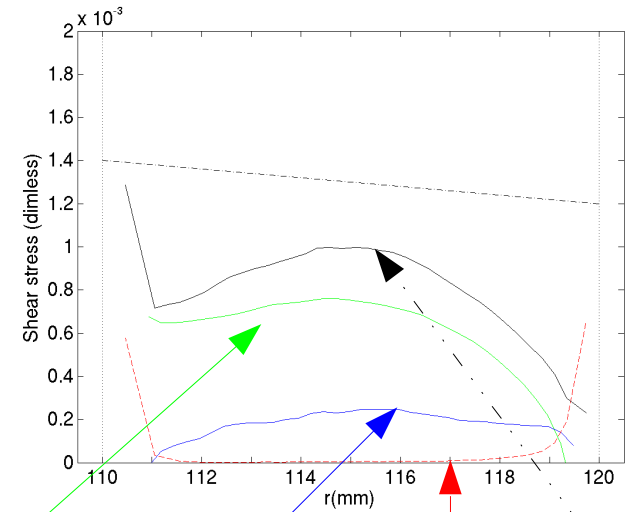
Main contribution to transport



$$v_\theta' \approx 0,03 \quad v_r' = v_z' \approx 0,02$$



Mean profile



Angular momentum balance : $\int_{\Sigma} \rho r V_\theta V_r ds + \int_{\Sigma} \rho r \langle v_\theta' v_r' \rangle ds + \mu \int_{\Sigma} r^2 \partial_r \left(\frac{V_\theta}{r} \right) ds = \Gamma$

Small fluctuations $v_\theta' \approx 0,03 \quad v_r' = v_z' \approx 0,02$

Model for the secondary flow

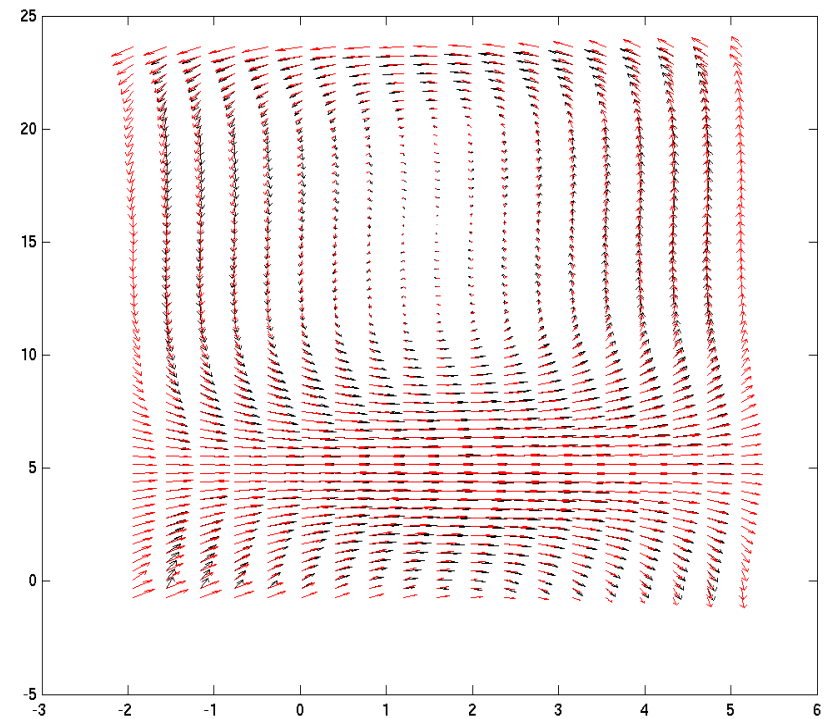
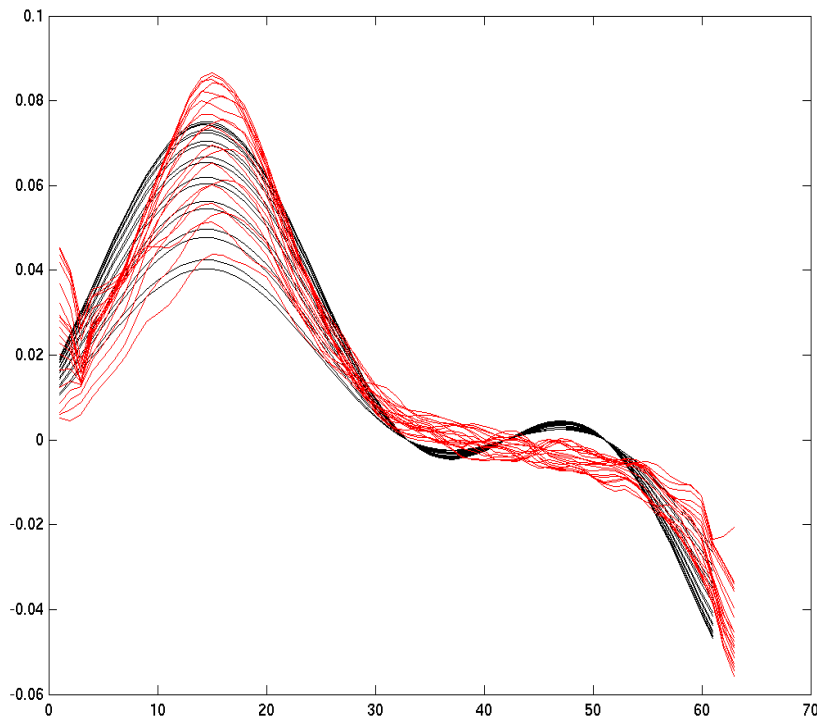
To quantify the secondary flow,
we fit the stream function:

$$\Psi = \sin\left(\pi \frac{(r-r_0)}{d}\right) \times \left(A_1 \sin\left(\pi \frac{(z-z_0)}{l}\right) + A_3 \sin\left(3\pi \frac{(z-z_0)}{l}\right) \right)$$

Fit parameters

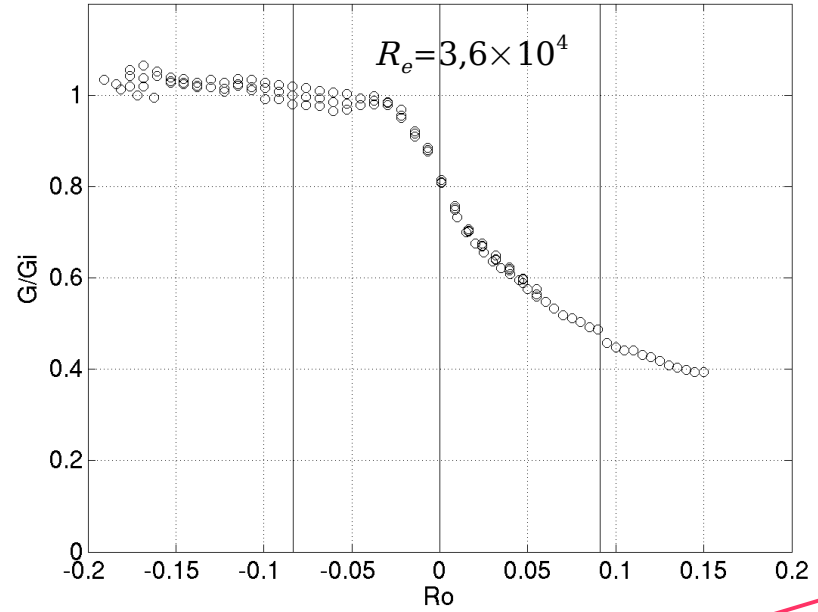
- A_1
- A_3
- l
- z_0
- r_0

Gives roll height (l) and strength of secondary motions.



Example : Experimental U, fitted U

Quantitative study of the transition at a fixed Reynolds number



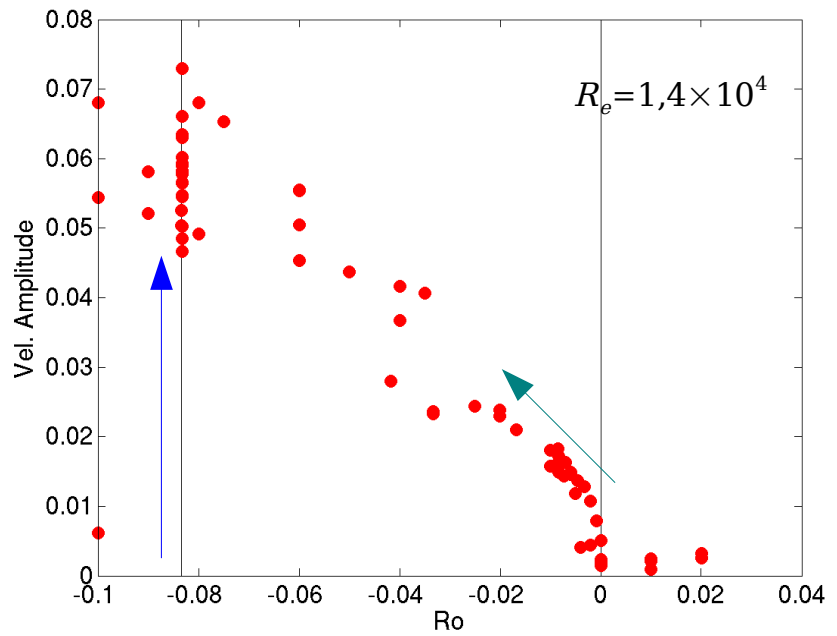
Torque at $Re = cte$:
 ◆ Constant around inner
 ◆ Smooth evolution

Amplitude of radial velocity based on fit

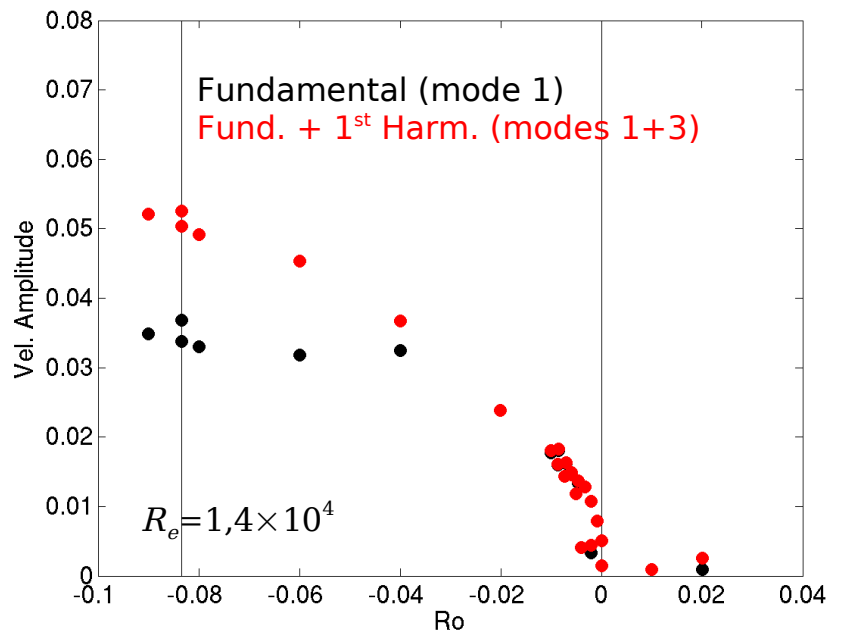
$R_\Omega < 0$ Secondary flow

Transient behaviour (coming next)

No hysteresis,
 qualitative change around $R_\Omega \simeq -0,03$
 (elongated rolls)



All points



20 mins. Stabilized experiments

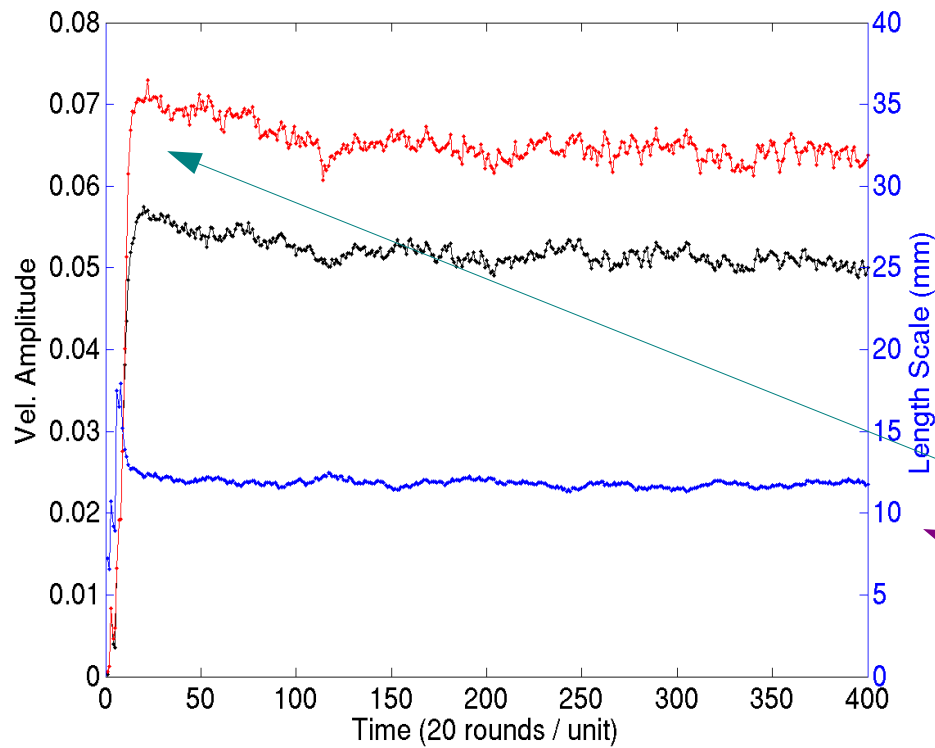
Transient experiments

- Laminar Taylor Vortices flow is known to depend on starting conditions
- Spread of data in our experiments

Inner alone, starting from rest, to $R_e = 1,4 \times 10^4$
(acceleration : $0,05 \text{ m.s}^{-2}$)

Overshoot, then relaxation

Final length = 1,2 gap widths.

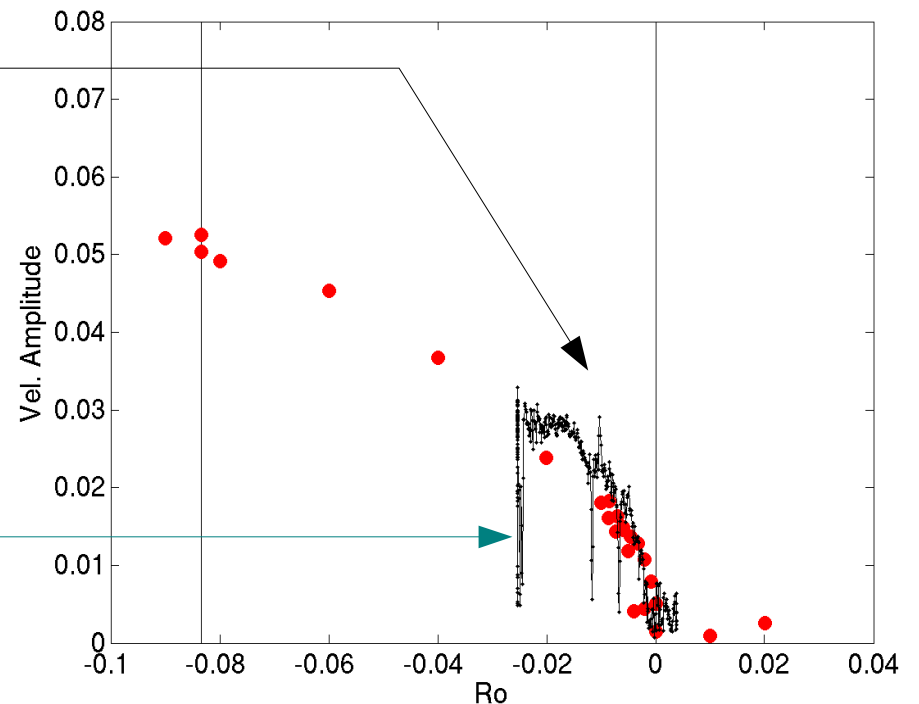


From Counterrotation to $R_\Omega = -0,025$

At a constant $R_e = 1,4 \times 10^4$

Acceleration $A \simeq 1 \times 10^{-4}$

Low peaks are physical
rolls disappear, are reversing...
(see Movie)



Conclusions & Perspectives

- We realized a Taylor-Couette facility for quantitative torque and velocity measurements.
- The counterrotation seems to be the threshold for the onset of a mean secondary flow on the turbulent Taylor-Couette flow.
- This transition seems smooth (supercritical ?).
- Next step : study of direct transition to turbulence in the subcritical (outer cylinder alone) regimes.

This work was made possible by financial support of Fundamenteel Onderzoek der Materie (Dutch national research) and Unilever corp. research

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**

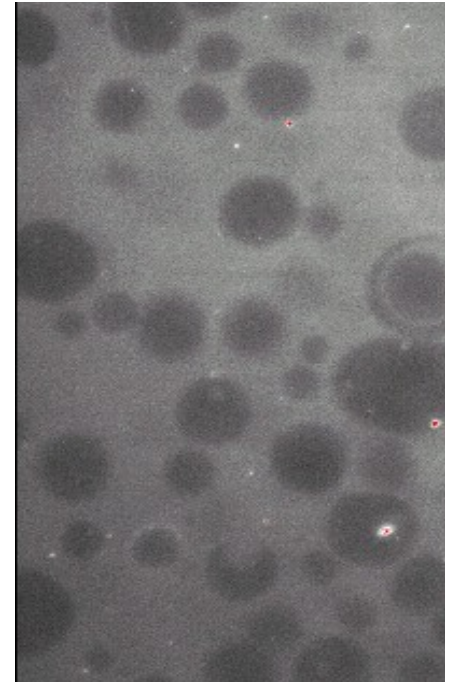
Oil extraction, food, chemical industry



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.

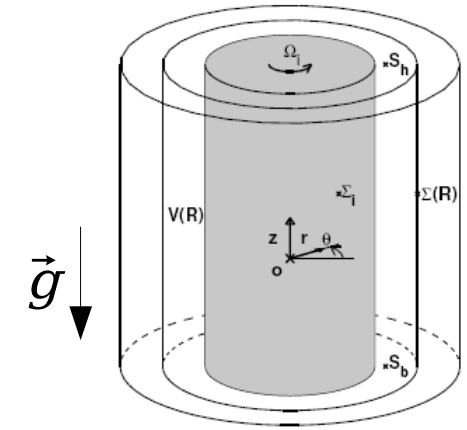
A **model shear-flow** : **the turbulent Taylor-Couette flow**

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 $\rho=1550 \quad \mu=2 \cdot 10^{-3} \quad \nu=1,3 \cdot 10^{-6} \quad R.I.=1,445$

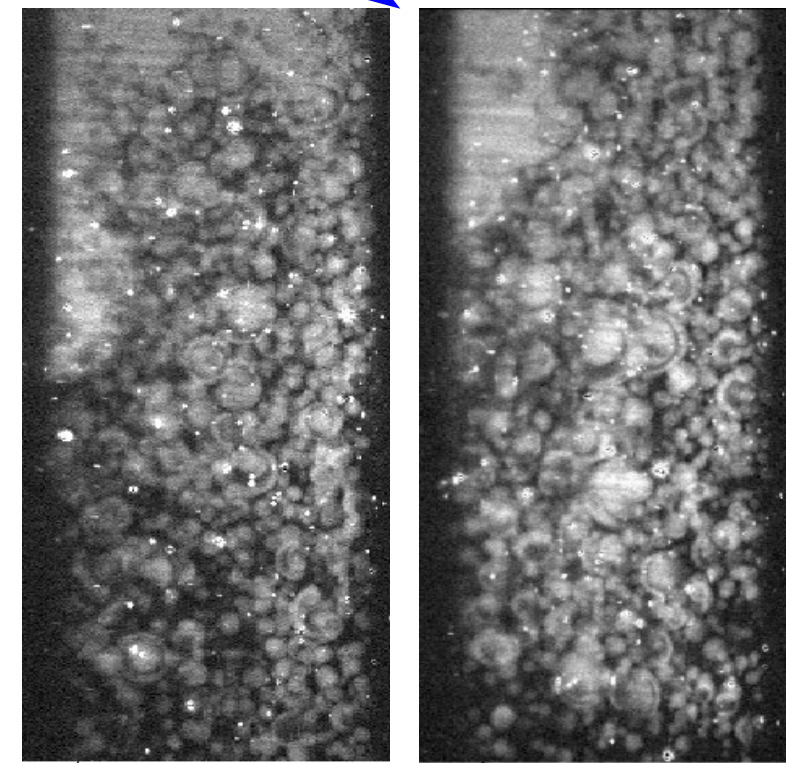
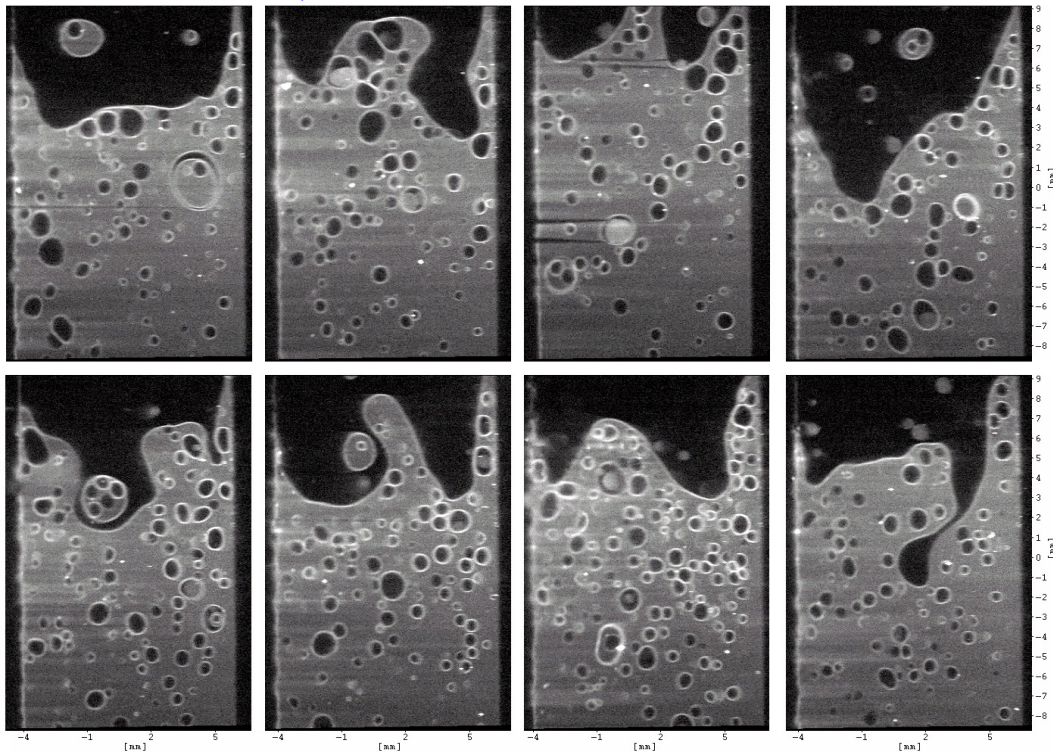


At rest : two layers

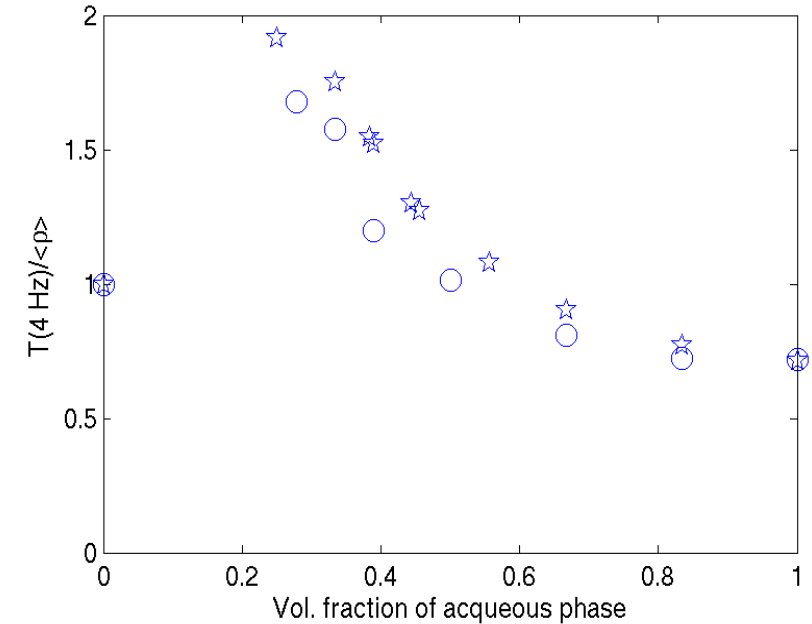
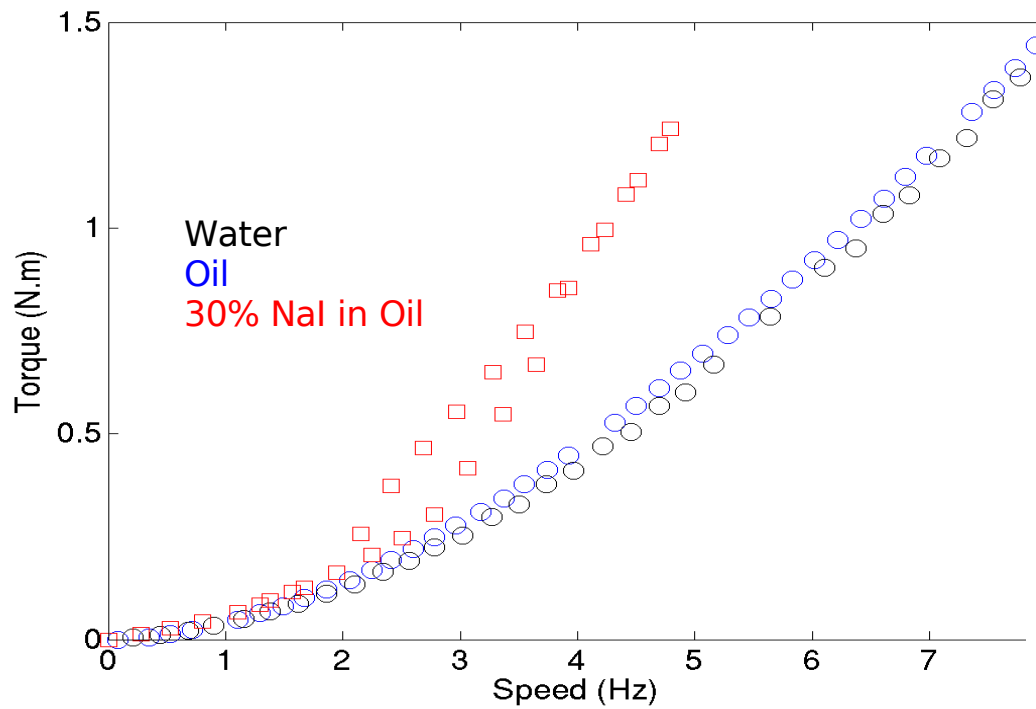
Counterrotating at 2Hz : dispersion starts

30% NaI in Oil

Counterrotating at 3Hz : concentrated dispersion



Quantitative measurements : Evolution of the torque



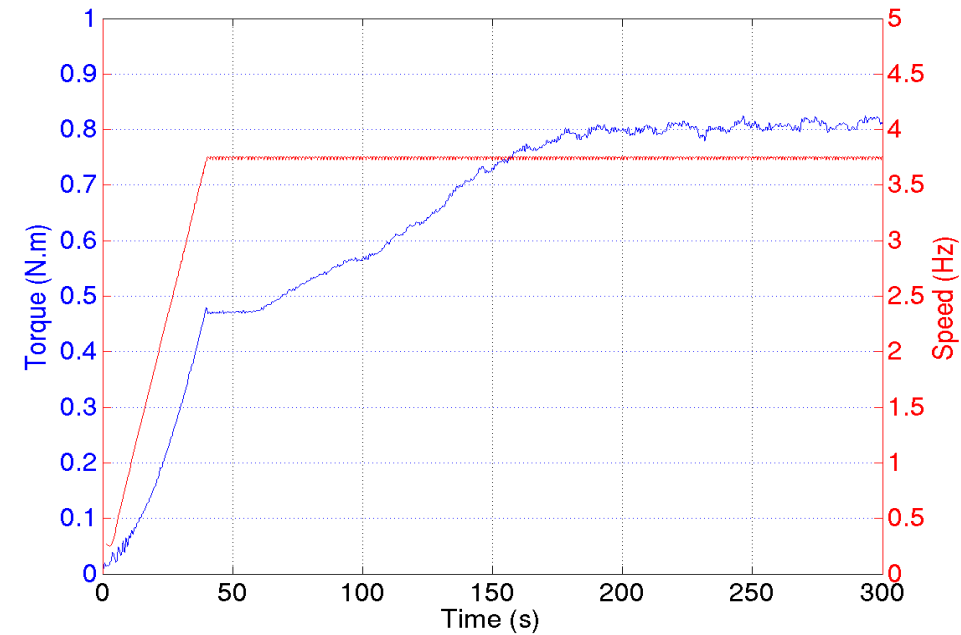
Relevant
parameters :

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.
Possibility to study a Subcritical transition to turbulence.
 $R_\Omega < -1$; $R_\Omega > 1/\eta - 1$
- Stereoscopic PIV : link with torque scaling.
- Two-phase flow : Effective viscosity,
Droplets distribution.
Long time behaviour ?

