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Efficient heat transport by Elastic Turbulence

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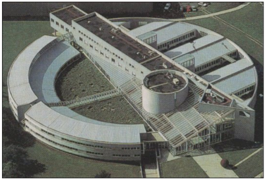
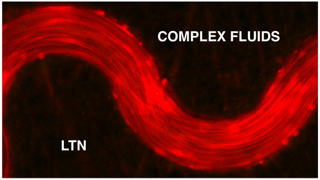
SFT day, 19th of November 2015, Paris





Related publication

"Efficient heat transfer in a regime of elastic turbulence", B. Traore, C. Castelain, T. Burghelea, *Journal of Non Newtonian Fluid Mechanics* **223** (2015) 62 – 76

Heat transfer in fluids: getting beyond the conduction

- The thermal conduction is the"natural" mechanism of heat transport in fluids.
- The thermal conduction is "slow": $\tau_c = \frac{\text{Characteristic Length Scale}^2}{\text{Thermal diffusivity}} \approx 10^3 - 10^5 s.$

One clearly needs to resort to other "ways" of transporting heat within fluids...

- Inertial turbulence? Sometimes not very practical (high *Re*), *e.g.* in a microchannel.
- Laminar chaotic advection? Sure, but it needs a special design of the flow channel and/or forcing conditions.

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Linear flexible polymers in solutions: ELASTIC NONLINEARITY

$$\frac{d\vec{V}}{dt} + \cancel{\underbrace{\vec{V}\nabla\vec{V}}_{\text{Inertial Nonlinearity}}} = -\frac{\nabla p}{\rho} + \frac{\eta_S}{\rho}\Delta\vec{V} - \underbrace{\frac{\tau_p}{\rho}}_{\text{Elastic Nonlinearity}}$$

Constitutive equation:

$$\tau_p + \lambda\frac{D\tau_p}{Dt} = -\eta_p\left[\nabla\vec{v} + (\nabla\vec{v})^T\right]$$

And... here is where the elastic nonlinearity comes from:

$$\frac{D\tau_p}{Dt} = \frac{\partial\tau_p}{\partial t} + (\vec{v}\nabla)\,\tau_p - (\vec{v}\nabla)^T\,\tau_p - \tau_p\,(\nabla\vec{v})$$

Inertia shall play no significant role during this movie: the nonlinear elasticity sets the "game"

The control parameter: the Weissenberg number

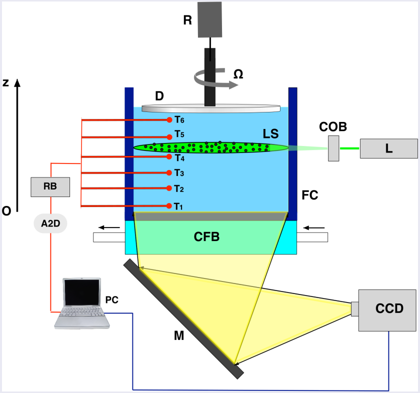
$$Wi = \frac{\text{Elasticity}}{\text{Viscous Disipation}} = \lambda \nabla v$$

Episode One

Heat transfer by ET in a **macroscopic** von Karman swirling flow (PhD work of Boubou Traore)

Experimental Setup, Modus Operandi

von Karman Setup



Several points to note

1. To avoid triggering the thermal convection, we cool from below.
2. The cell is mounted on a rheometer: accurate measurements of the power injected into the system: $P = T\Omega$.

Why looking at a macroscopic von Karman flow? - some expectations

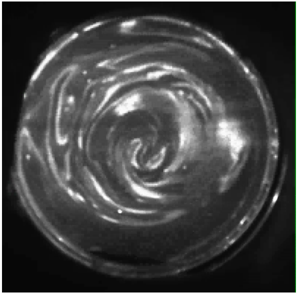


Figure: *Phys. Fluids* ***19*** *(2007), Phys. Fluids* ***15*** *(2005), Europhys. Lett.,* ***68*** *(2004)*

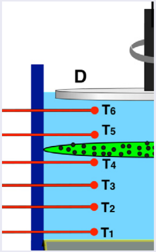
E.T. mixes well a passive scalar

- A roughly 1000 times increase in mixing efficiency
- Ideal realisation of the Batchelor regime of mixing

Experimental Methods

Assessment of the efficiency of the heat transfer

Point wise measurements of the temperature



Under the hood:

1. Six thermocouples are evenly spaced along the vertical axis at $r = R_c/2$: **YES, they will perturb the flow, but don't worry about this right now!**.
2. We acquire long (several τ_c) T series.
3. The local efficiency of the heat transfer is inferred from the local rate of change of T.

NOTA BENE

Because we want TOTAL control and we care about the tax payer ($)) we do not rely on ready flow visualisation solutions: we took it from the screw to the publication level.

Space-Time characterisation of the flow structure

Time resolved measurements of the flow fields using a **home-made DPIV** technique with several "exotic" ingredients:

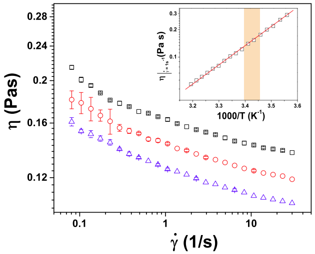
Under the hood:

1. background subtraction, morphological elimination of the out of focus image features
2. adaptive inter-frame, sub-pixel interpolation
3. median filtering, signal to noise rejection of outliers
4. spline interpolation of individual flow fields and subsequent differentiation

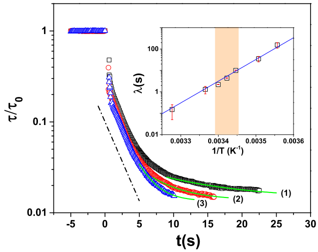
Rheological and thermal properties of the polymer solutions

Polymer solution

- 150 ppm polyarcylamide (PAAM) $M_w = 22 \cdot 10^6 Da$ in 65% sucrose solvent, $\rho = 1200 kgm^{-3}$ - $\kappa_s = 2.21 \cdot 10^{-7} m^2 s^{-1}$, $\kappa = 1.31 \cdot 10^{-7} m^2 s^{-1}$, $t_d = H^2/\kappa \approx 25714s$



(a)



(b)

Figure: 2(a) Shear viscosity 2(b) Relaxation time

Summing this up:

- An Arrhenius T scaling is found for both the shear viscosity and the largest relaxation time, but the activation energies are different:

$$\eta \propto e^{\frac{E_\eta}{RT}}, \ \lambda \propto e^{\frac{E_\lambda}{RT}}, \ E_\eta \neq E_\lambda$$

NOTA BENE:

In the absence of buoyancy T is expected to behave as a *"passive scalar"*.

But...

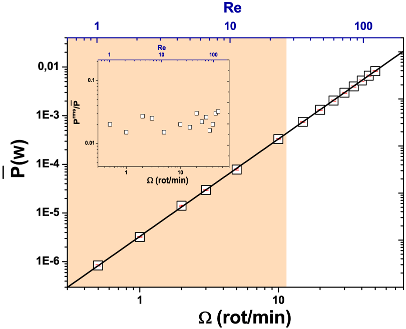
... in the presence of a strong T dependence of the elastic stresses ...

IS THE PASSIVE SCALAR BEHAVIOUR STILL GRANTED?

Observation of the Elastic Turbulence

The Reynolds number: $Re = \frac{\Omega R_c^2 \rho}{\eta(\dot{\gamma})} \leq 25$.

Is it too large (any inertial instabilities)? - only one way to find out I guess.

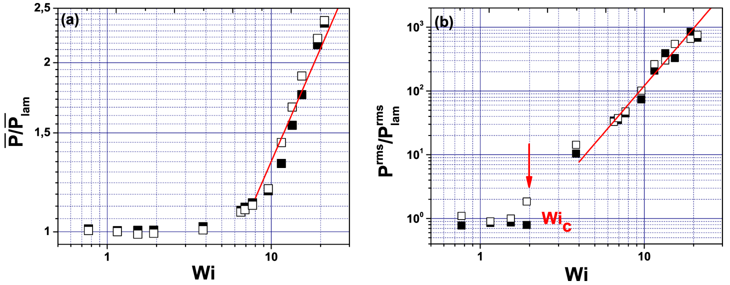


- Time averaged power $\bar{P} = \Omega \bar{T}$ measured with the solvent alone. Full line, analytical prediction: $\bar{P} \propto \Omega^2$
- No physical fluctuations of P (see insert), just 2% instrumental noise

To conclude: **No significant inertial contributions observed for $Re \leq 25$.**

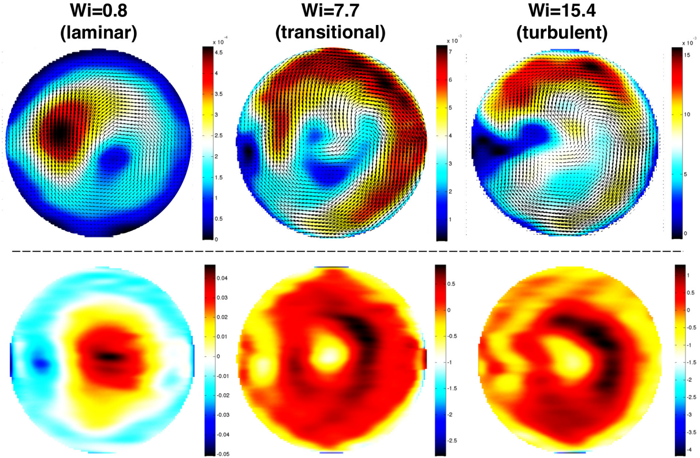
Observation of the Elastic Turbulence

Measurements of the time averaged reduced power $\bar{P}/P_{lam}$ (left) and power fluctuations (right) at various Wi



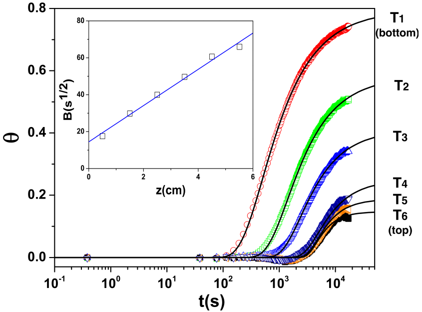
To conclude: **The transition to Elastic Turbulence is marked by a sharp increase of the flow resistance and of the power fluctuations, features that are common to a random flow. Again, nothing to do with inertia!**

Flow structure in a regime of Elastic Turbulence: top line - mean flow field, bottom line - mean vorticity



Heat transfer within the solvent alone

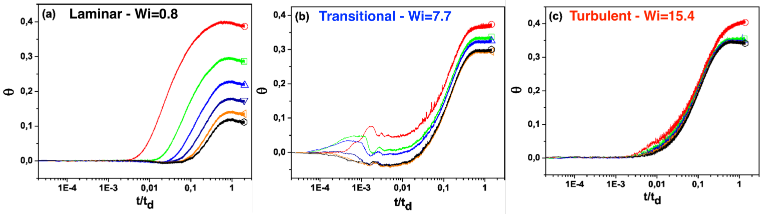
Reduced temperature: $\theta = \frac{T_0 - T}{T_0 - T_b}$, T_0 - room temperature, T_b - temperature of the cooling bath.



- A clear vertical gradient is observed - spatially inhomogeneous T field.
- No "random" component of the T signals is observed.
- Each series can be "formally" fitted by a 1D solution: $\theta = A \cdot erfc\left(\frac{B}{\sqrt{(t)}}\right)^C$.

In the absence of both elasticity and inertia, the heat transfer is "poor". Can we do better than that?

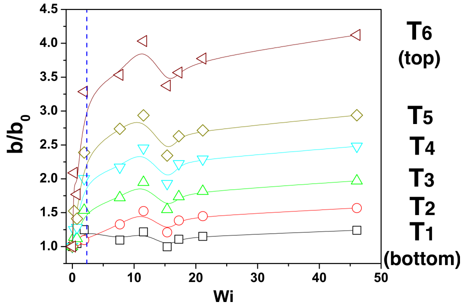
Heat transfer within the polymer solution: *Wi* - control parameter.



- Below the onset of the elastic instability, $Wi = 0.8 < Wi_c$, the heat transfer scenario is similar to that observed with the solvent alone: spatially inhomogeneous T field, non fluctuations, poor transport overall.
- T fluctuations and improved heat transport observed within the transitional regime $Wi = 7.7$.
- Vertically homogeneous T distribution and strong T fluctuations are observed in a regime of elastic turbulence, $Wi = 15.4$

Efficiency of the heat transfer by Elastic Turbulence

Fit the reduced time series $\theta(t)$ by: $\theta \propto a + \mathbf{b} ln\left(\frac{t}{t_d}\right)$. Local transfer intensity: **b**.



Several points on the efficiency

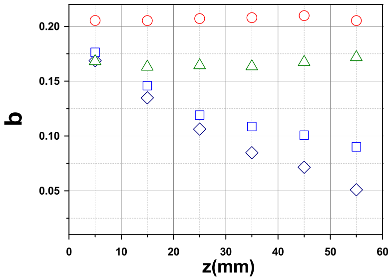
- No efficiency increase with Wi near the bottom plate (this is the heat sink, right?)
- A nearly **four fold efficiency increase** is observed near the top disk

Summing up this part:

The **Elastic Turbulence** may increase the efficiency of the heat transfer in the absence of inertia up to 400%.

Efficiency of the heat transfer by Elastic Turbulence: spatial dependence

$$\theta \propto a + \mathbf{b} ln\left(\frac{t}{t_d}\right)$$

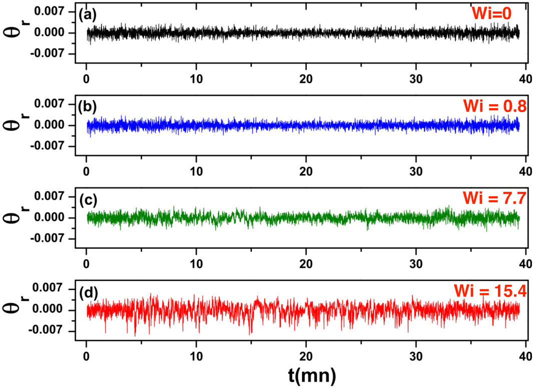


Several points on the efficiency

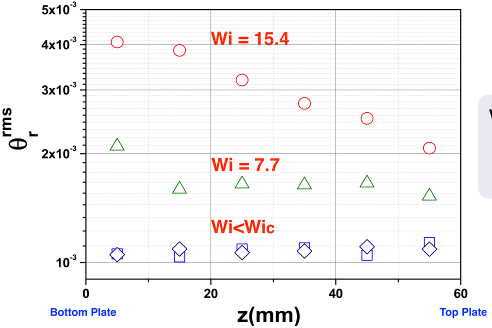
- Strong anisotropy (z - dependence) of the efficiency in a laminar state (rhombs) - quite obvious (you remember where the heat sink is, right)?.
- Spatially homogeneous transport efficiency in a regime of elastic turbulence (note the red circles)

Statistical properties of the heat transfer by Elastic Turbulence

Look at the "fluctuating" part of the reduced temperature time series - just subtract the pedestal of the signal.



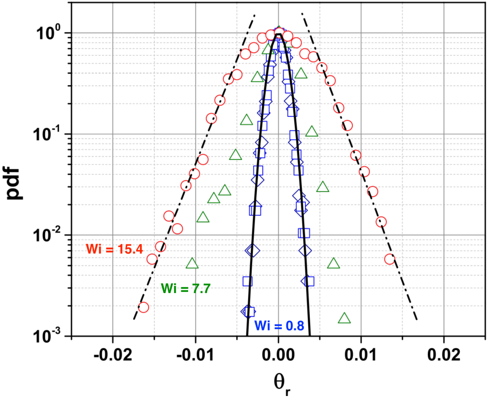
Statistics of temperature fluctuations



Within the ET regime strong T fluctuations are observed near the bottom plate

A strong spatial inhomogeneity of T fluctuations is obsevered.

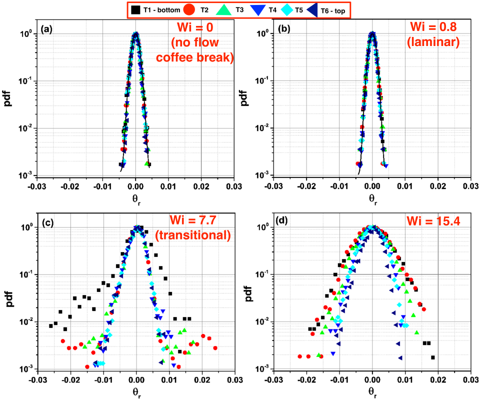
Passive or active scalar? - that is the question!



Note

A first signature of the passive scalar behaviour: exponential tails of the pdfs.

Space dependence of the statistical properties

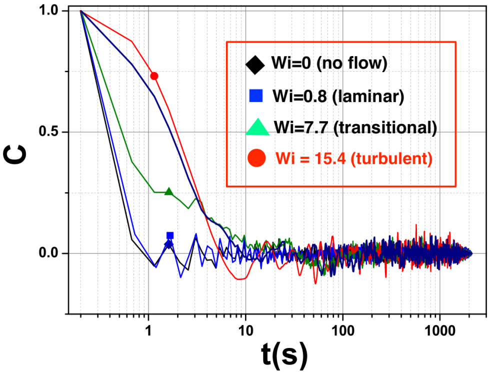


Note

Strong intermittency observed near the bottom plate (the squares and circles)

The statistical distribution of T fluctuations is strongly inhomogeneous along the z direction.

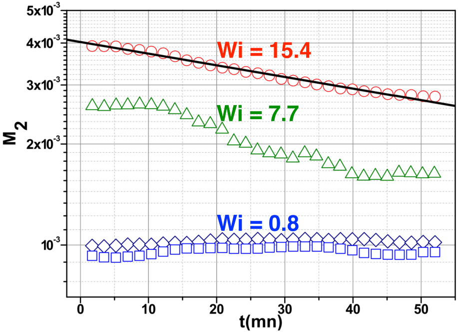
Decay of correlations of the T fluctuations



Note

In a regime of ET the correlation time is set by the relaxation time of the polymer

Passive or active scalar? - that is the question!

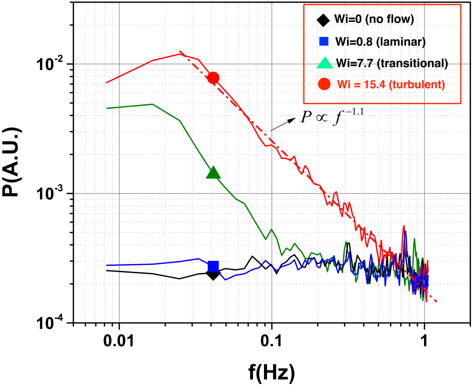


Note

A second signature of the passive scalar behaviour:
exponential decay of the variance

$$M_2 \propto exp(-t/t_{decay}),\ t_{decay} = 7500\ s \approx t_c/3$$

Decay of spectra of the T fluctuations



Note

As in the case of a passive scalar, a power law decay of the spectrum is observed: $P \propto f^{-1.1}$

Episode Two

Heat transfer by ET in a **microscopic** curvilinear flow
(ongoing postdoctoral research of Dr. Antoine Souliès - started April 2015)

Observation of Elastic Turbulence in a micro-channel

- $200\mu m x 200\mu m$ curvilinear micro-channel (also "home made" in the "low budget" spirit!)
- $\mathbf{Re \approx 10^{-4}}$ - no inertia playing in this movie, remember?

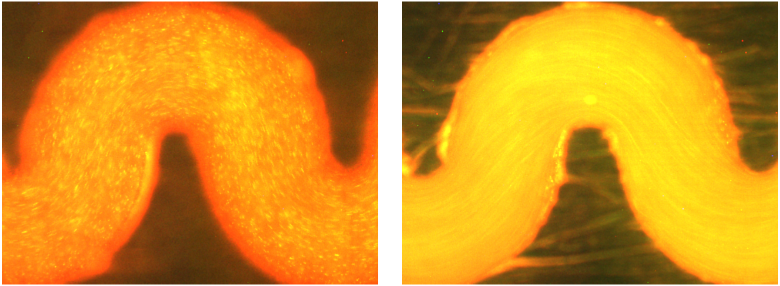
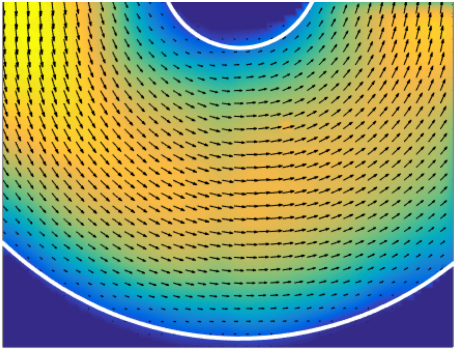


Figure: 3(b) Laminar Case 3(a) Elastic Turbulent Case

Some extra tricks under the hood...

Space-time investigation of the flow fields.

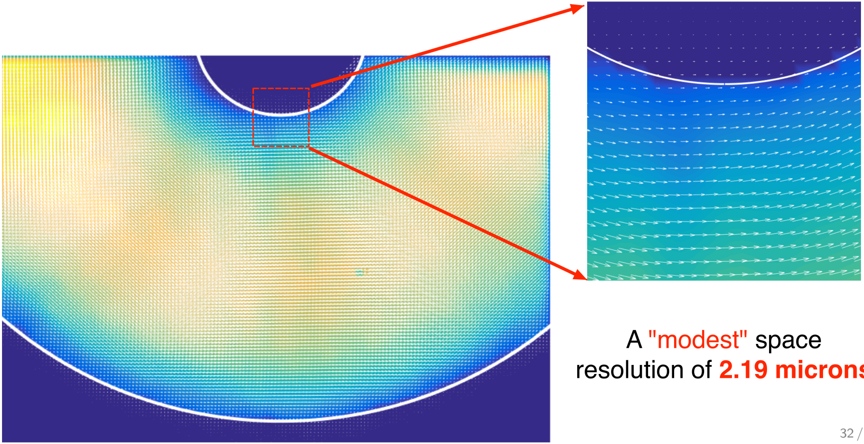


The "Black Magic" toolbox we developed

- Home made state of art high resolution micro-PIV: down to $3\mu m$ space resolution
- Long time series of flow fields: roughly 100 polymer relaxation times

More (but not all!) about our *"black magic"* tricks

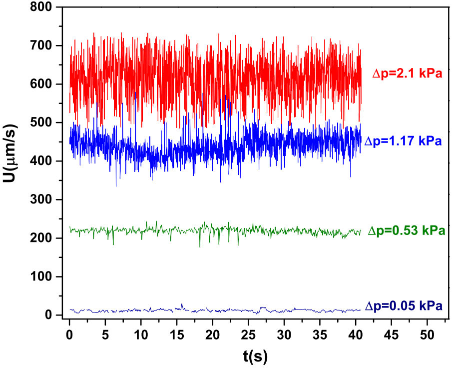
Did I mention High Resolution flow field measurements?
I surely did, and I was serious about - Antoine too!



A "modest" space resolution of **2.19 microns**

The transition to Elastic Turbulence in a serpentine micro-channel

Measure long time series of flow fields, monitor the level of fluctuations.



Nota Bene

- Beyond a critical pressure drop strong fluctuations are observed, yet **Re** $<<$ **1**!

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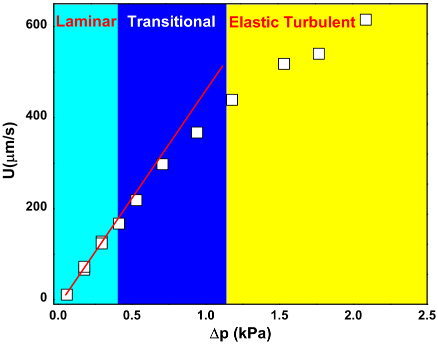
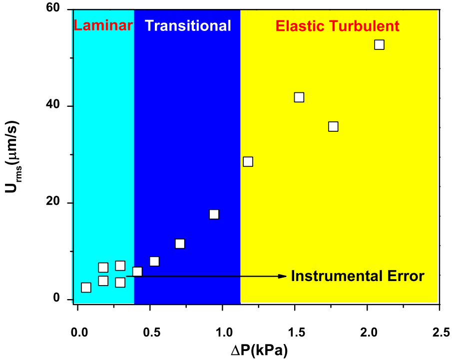


Nota Bene

- Beyond a critical pressure the average speed goes sublinear: secondary flow, right?

The transition to Elastic Turbulence in a serpentine micro-channel

Quantify the level of fluctuations past the onset of the elastic instability: instrumental error roughly 4%.

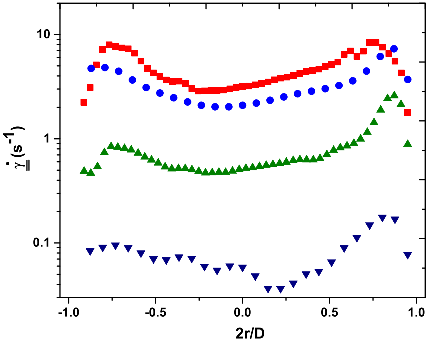


Nota Bene

- Beyond a critical pressure drop strong fluctuations are observed, yet **Re** $<<$ **1**!

Define properly the Weissenberg number: first, get a proper scale of the velocity gradients

Look at the profiles of the invariant of the velocity gradients tensor

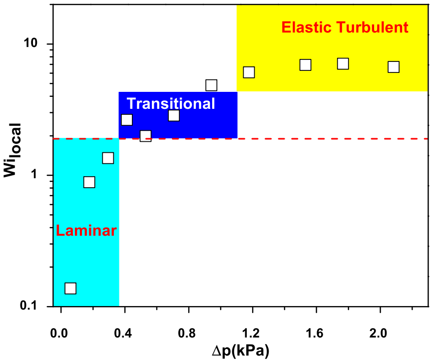


Nota Bene

- The local peaks of the profiles indicate the position of the elastic stresses boundary layer

Define "locally" the control parameter - rely on the state of art flow characterization

Use the maximal value of the measured second invariant of the velocity gradient tensor: $\mathbf{Wi_{local}} = \lambda \dot{\underline{\gamma}}$



Nota Bene

- The local Weissenberg number saturates in a regime of Elastic Turbulence.

Acknowmedgments

People

- **Gwénäel Biotteau**: design and machining of the von Karman flow system, design and micro-milling of the micro-channels.
- **Julien Aubril**: interfacing, data acquisition for the micro-channel experiments
- **Christophe Le Bozec**: interfacing, data acquisition for the von Karman swirling flow experiment

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