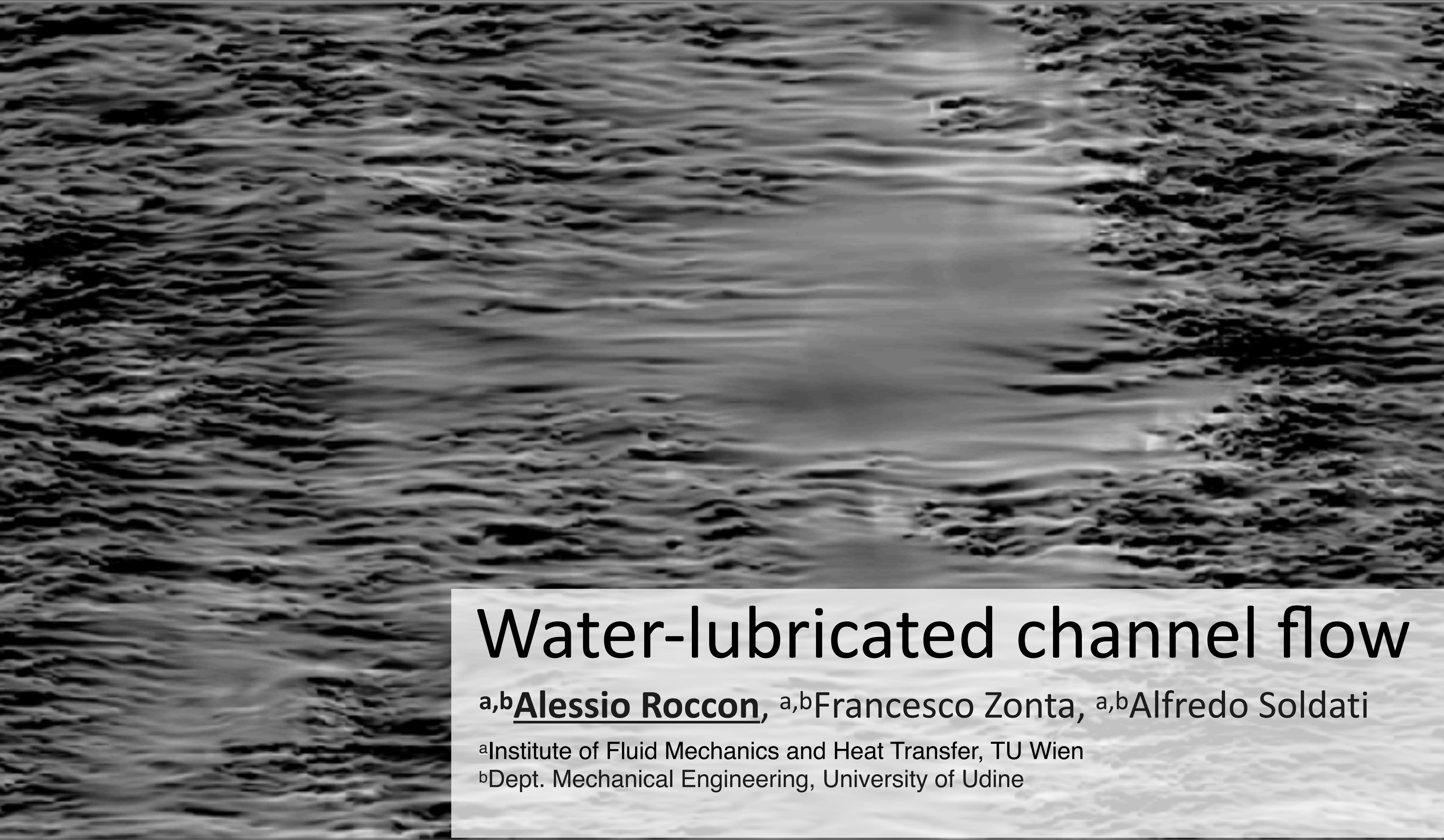
COMETE
Final Conference
ESTECO, Trieste



Water-lubricated channel flow

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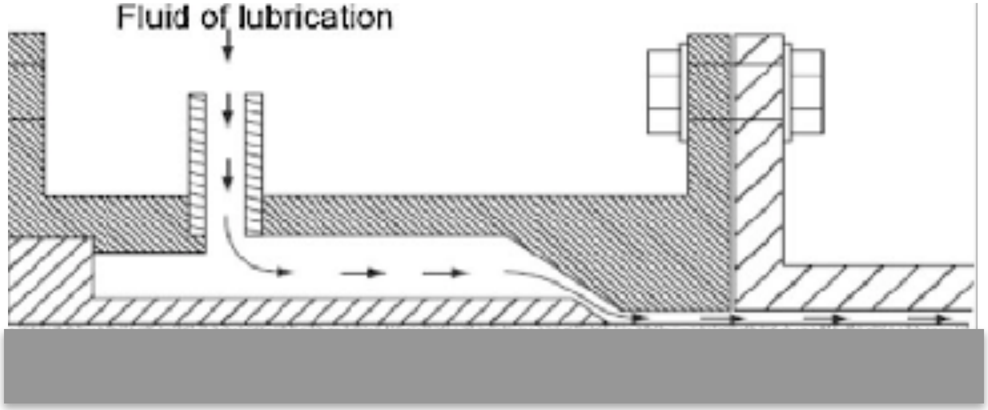
Figure: Streaks in the lubricating layer of a water-lubricated channel.

Core Annular Flow



Main idea:
Injection of a thin lubricating layer to favour the transport of a more viscous main layer.

“There is a strong tendency for two fluids to arrange themselves so that the low-viscosity constituent is in the region of high shear. This gives rise to a kind of a gift of nature in which the lubricated flows are stable, and it opens up very interesting possibilities for technological applications in which one fluid is used to lubricate another“.

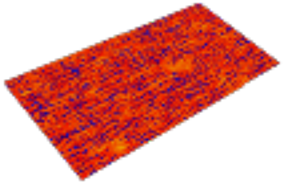
We have a viscosity stratified configuration, turbulence behaviour? Interface dynamics?
Can we simulate this configuration?

Credit: ALFA Research Group
Joseph et al., Core-anular flows, ARFM (1997)

Numerical Method
DNS + PFM

We couple direct numerical simulation (DNS) of the Navier-Stokes equations with a two-order parameter Phase-field Method (PFM) to describe the interface topology and the surfactant.

Flow field:



$$\frac{\partial u_i}{\partial x_i} = 0,$$

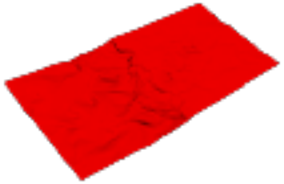
Pressure gradient

Viscosity contrast

Surface tension forces

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -p_x \delta_{xi} - \frac{\partial p}{\partial x_i} + \frac{1}{Re_\Pi} \frac{\partial}{\partial x_j}\left[\eta(\phi)\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right] + \frac{3Ch}{\sqrt{8}We_\Pi} \frac{\partial \left[f_\sigma(\psi)\tau^c_{ij}\right]}{\partial x_j}$$

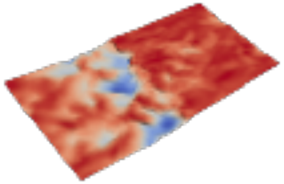
Interface:



$$\frac{\partial \phi}{\partial t} + u_i \frac{\partial \phi}{\partial x_i} = \frac{1}{Pe_\phi} \frac{\partial^2 \mu_\phi}{\partial x_i^2},$$

φ=+/- 1 in the two layers

Surfactant:

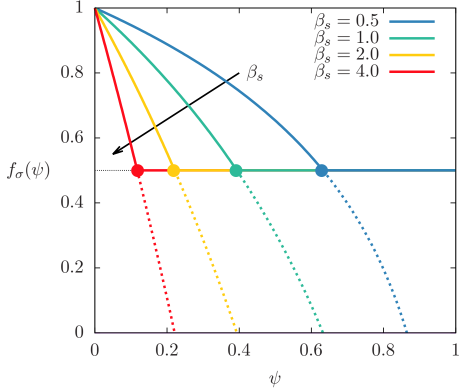


$$\frac{\partial \psi}{\partial t} + u_i \frac{\partial \psi}{\partial x_i} = \frac{1}{Pe_\psi} \frac{\partial}{\partial x_i}\left[\psi(1-\psi)\frac{\partial \mu_\psi}{\partial x_i}\right]$$

0 < ψ < 1 absence/saturation of surfactant

Langmuir EoS

$$\frac{\sigma}{\sigma_0} = f_\sigma(\psi) = 1 + \beta_s \log(1-\psi)$$



G. Soligo, A. Roccon, A. Soldati, Coalescence of surfactant-laden drops by Phase Field Method, JC. (2019).
G. Soligo, A. Roccon, A. Soldati, Breakage, coalescence and droplet size distribution of surfactant-laden droplets, JFM (2019).

CPI Simulations Details

Simulations of turbulent channel flow

Common approaches:

- Constant Flow Rate (CFR)
- Constant Pressure Gradient (CPG)

Study of DR with CFR and CPG might lead to some problems and influence the results:

- Different power injected
- Comparison is difficult

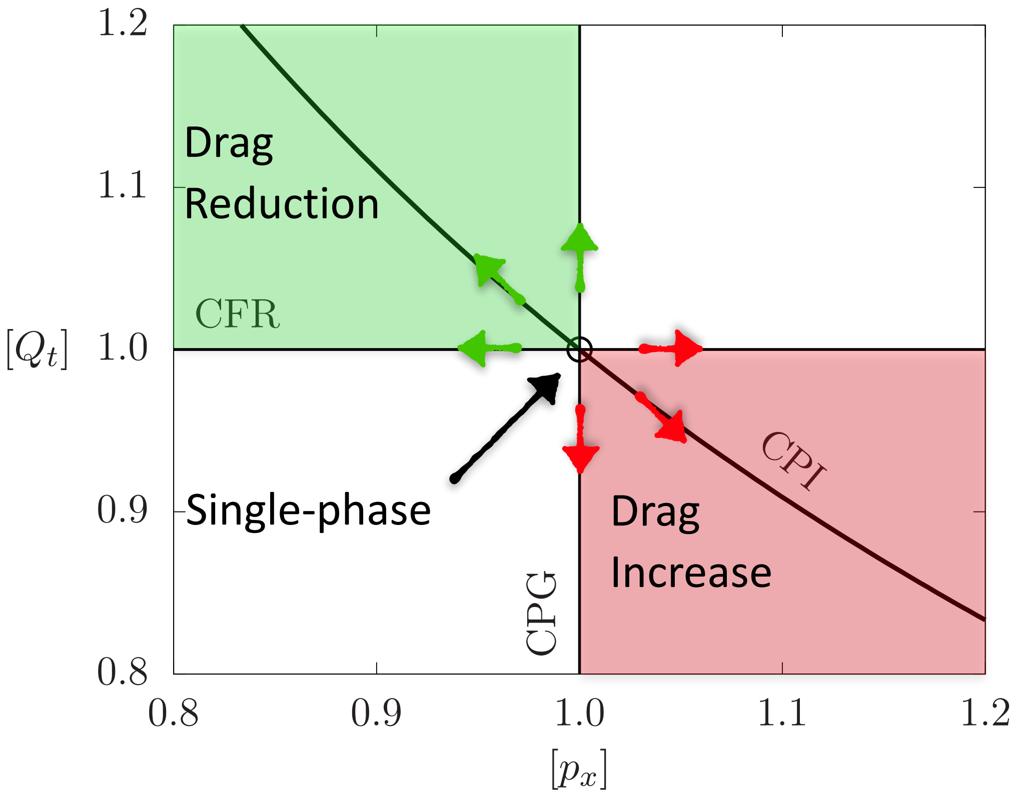
Third possible approach:

- Constant power input (CPI)

Power injected is kept constant adapting the mean pressure gradient to the flow-rate:

$$-p_x^{n+1} = \frac{3}{B Re_\Pi u_b^n}$$

Mean pressure gradient   Bulk velocity (Flow-rate)



Hasegawa et al., Numerical simulation of turbulent duct flows with constant power input, JFM (2014)
Roccon et al., Turbulent drag reduction by compliant lubricating layer, JFM-R (2019)
Roccon et al., Energy balance in lubricated drag-reduced turbulent channel flow, JFM (2021)

CPI Simulations
Simulation setup

Characteristic velocity based on the laminar bulk velocity (max. efficiency):

$$u_\Pi = u_b = \sqrt{\frac{B^2}{D}}\sqrt{\frac{P_p h}{3\eta_w}}$$

<u>Flow parameters:</u>

Reynolds number (inertia/viscous)

$$Re_\Pi = \frac{\rho u_\Pi h}{\eta_w} \simeq 80000$$

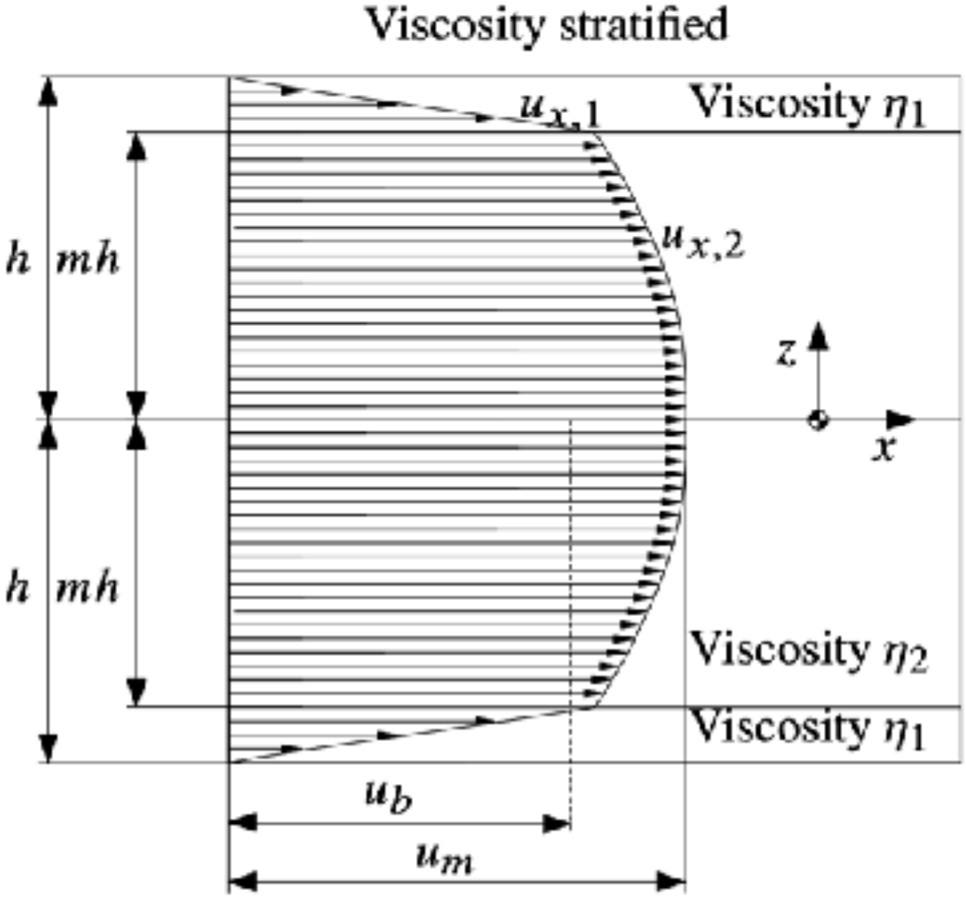
Weber number (inertia/interfacial)

$$We_\Pi = \frac{\rho u_\Pi^2 h}{\sigma_0} \simeq 1500$$

<u>Phase field parameters:</u>

$$Pe_\Pi = \frac{u_\Pi h}{\mathcal{M}\beta} \simeq 15000 \qquad Ch = \frac{\xi}{h} = 0.01$$

We fix the viscosity of the near-wall layers (water) and we change the oil viscosity:



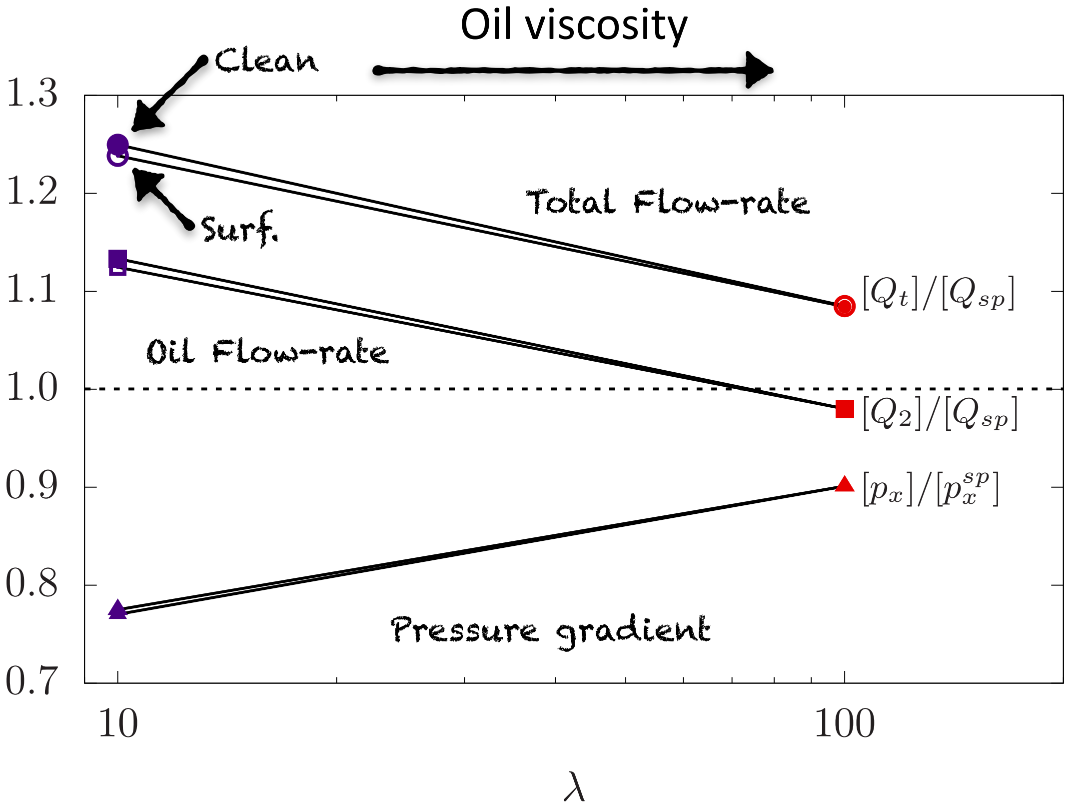
*Roughly corresponding to a shear Re_τ=1000.

**For the lubricated cases, Re, We and Pe are slightly different (different characteristic velocity)

Hasegawa et al., Numerical simulation of turbulent duct flows with constant power input, JFM (2014)
Roccon et al., Turbulent drag reduction by compliant lubricating layer, JFM-R (2019)
Roccon et al., Energy balance in lubricated drag-reduced turbulent channel flow, JFM (2021)

Results
Flow-rate and pressure gradient

Flow-rates and pressure gradient (normalised on single-phase results; water):



Full symbols = surfactant-free (clean)
Empty symbols = surfactant-laden

- Drag reduction (CPI approach)
  Flow-rate increases and at the same time the mean pressure gradient decreases.
- For all cases, total flow-rates increase and pressure gradients decrease (compared to a 100% water flow)
- Small difference between the surfactant-free and surfactant-laden cases (visible only for λ=10).

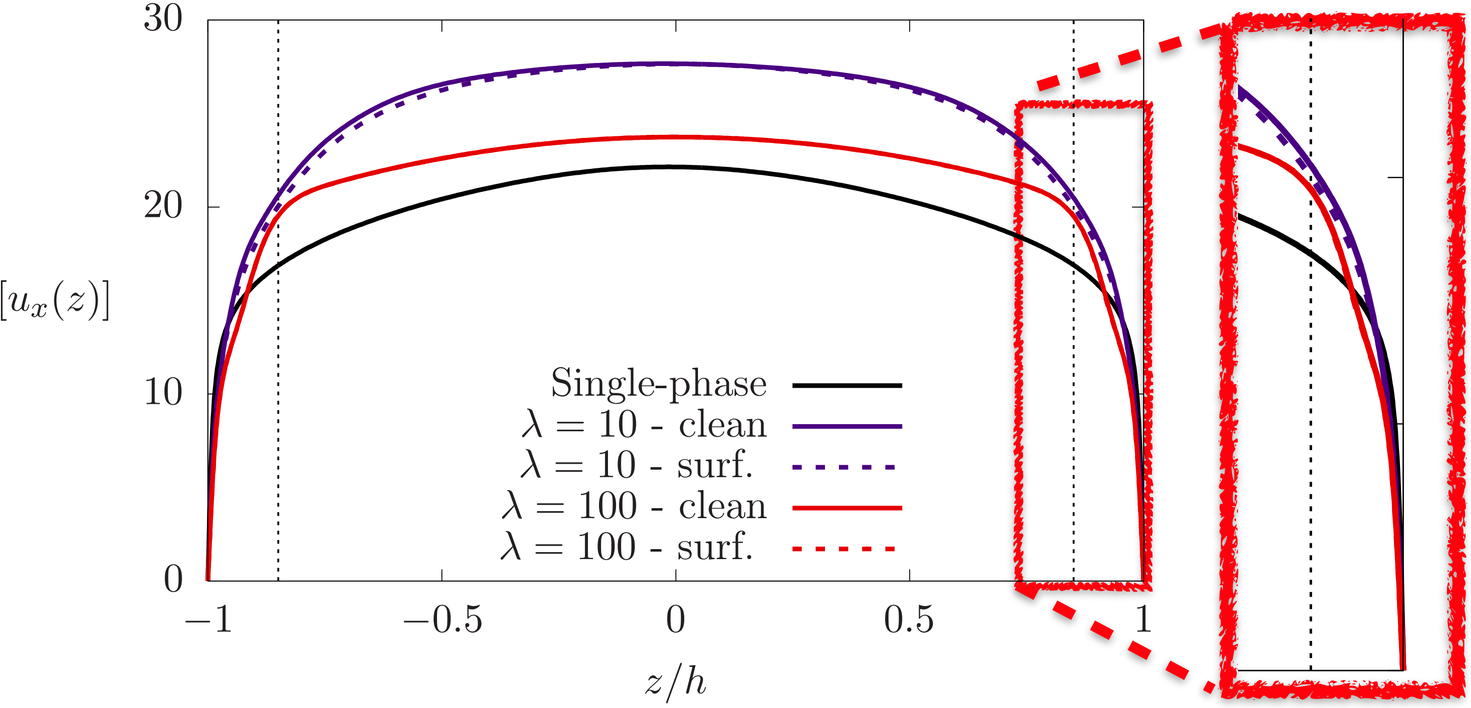
Velocity profiles?

$$\lambda = \frac{\eta_o}{\eta_w} = \frac{\text{Core (oil)}}{\text{Lubricating (water)}}$$

Results
Mean velocity profiles

Mean velocity profiles*:

CPI approach: higher flow-rates identify a “more laminar” state.



Near-wall behaviour is different between the two ratios. Flow seems “more turbulent” for λ=100 (smaller velocity). Less efficient transport, why?

Core: quasi-laminar behaviour for all cases.

Lubricating: turbulent? partial laminarization?

*Normalised using the single-phase velocity

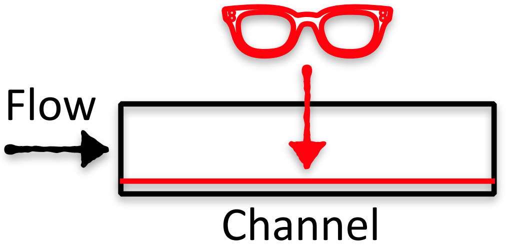
Let’s take a look at the flow behaviour in the lubricating layers.

$$\lambda = \frac{\eta_o}{\eta_w} = \frac{\text{Core (oil)}}{\text{Lubricating (water)}}$$

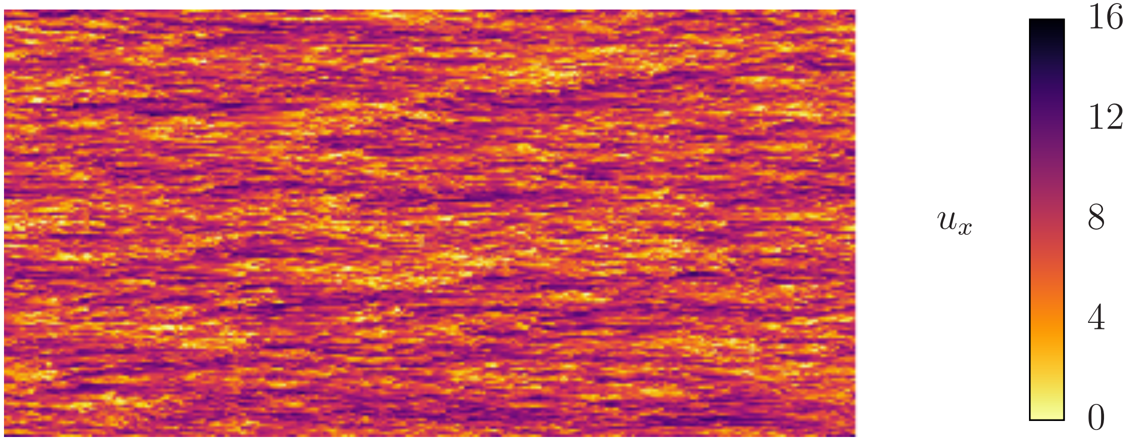
Qualitative view
Effect of viscosity ratio (clean)

We take a look at one slice located at z/h-=0.99 (10 w.u. from the wall, water layer).

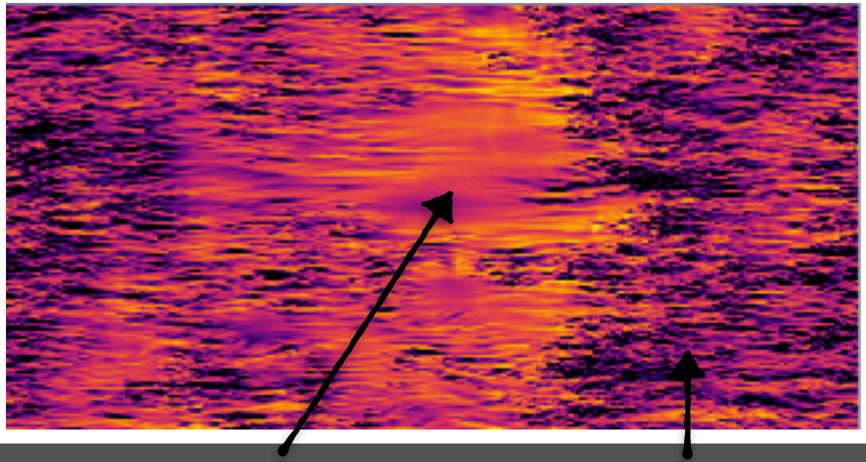
$$\lambda = \frac{\eta_o}{\eta_w} = \frac{\text{Core (oil)}}{\text{Lubricating (water)}}$$



- Single-phase flow:



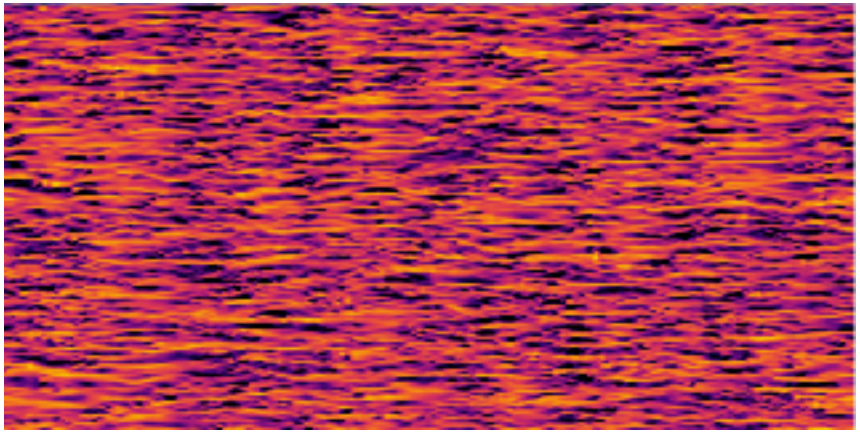
- λ=10 (moderate viscosity oil)



Laminar patches

Turbulence pockets

- λ=100 (high viscosity oil)

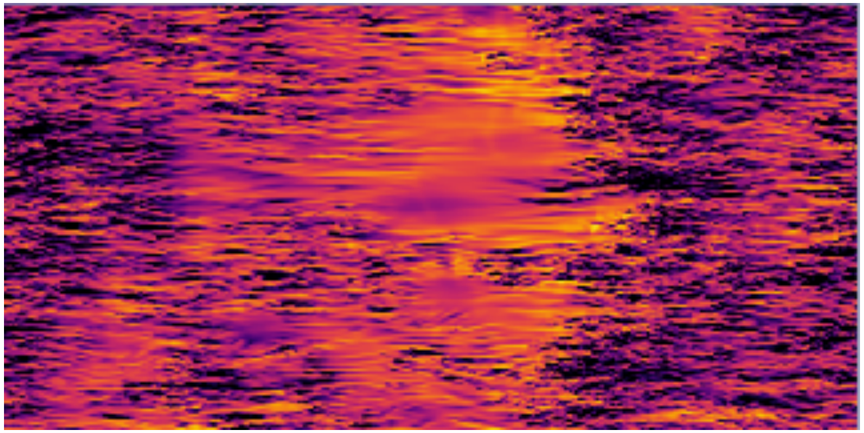


Turbulence activity is rather uniform
Lack of large scale fluctuations

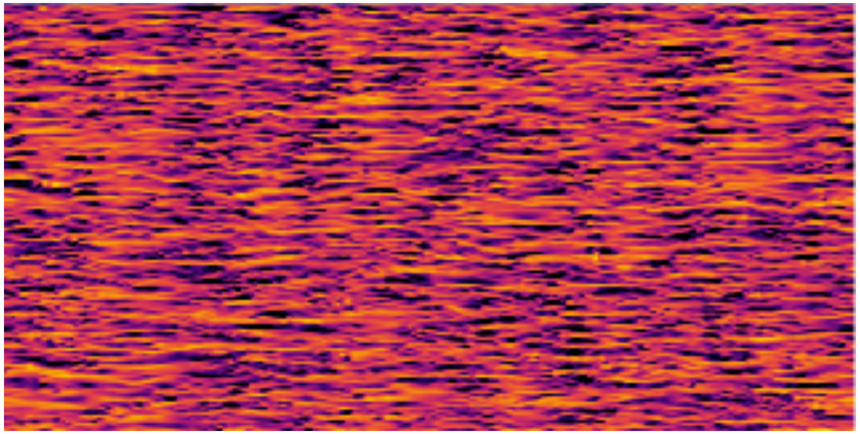
Qualitative view
Effect of surfactants

Slice located at z/h=-0.99 (10 w.u. from the wall).

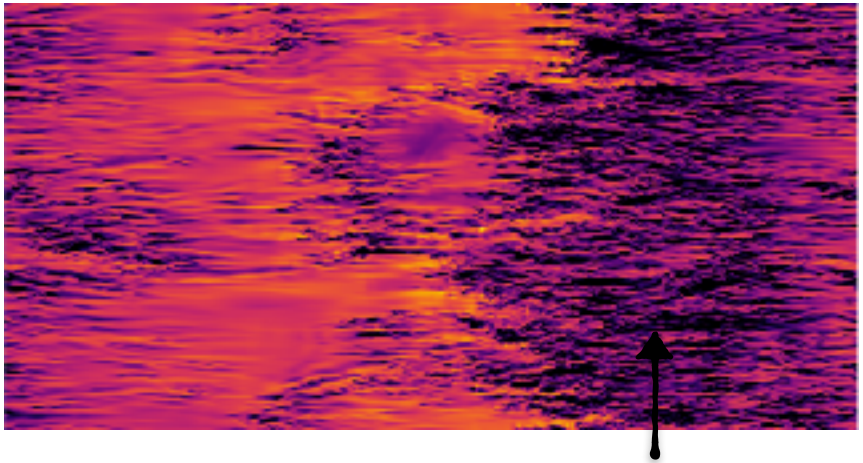
- λ=10 - clean, surfactant-free



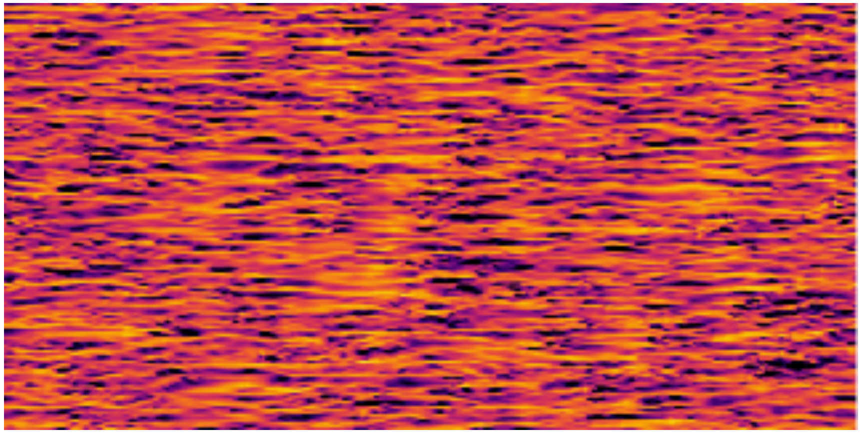
- λ=100 - clean, surfactant-free



- λ=10 - surfactant-laden



- λ=100 - surfactant-laden



Darker region, turbulence activity seems slightly enhanced

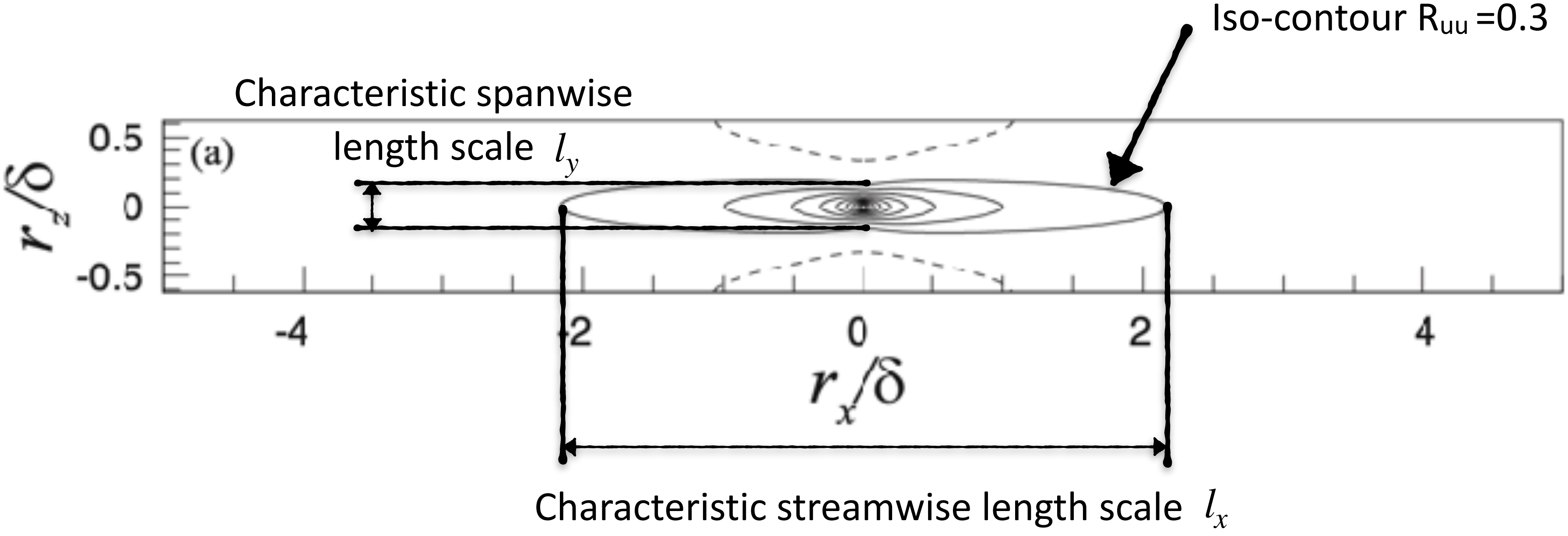
No significative changes between the clean and surf-laden case

Characteristic length scales
Streamwise correlation

To characterise the length scales of the flow, we compute the streamwise correlation:

$$R_{uu} = \frac{u'(\mathbf{x})u'(\mathbf{x}+\mathbf{\Delta x})}{RMS(u')^2}$$

For a single-phase turbulent flow, we obtain:



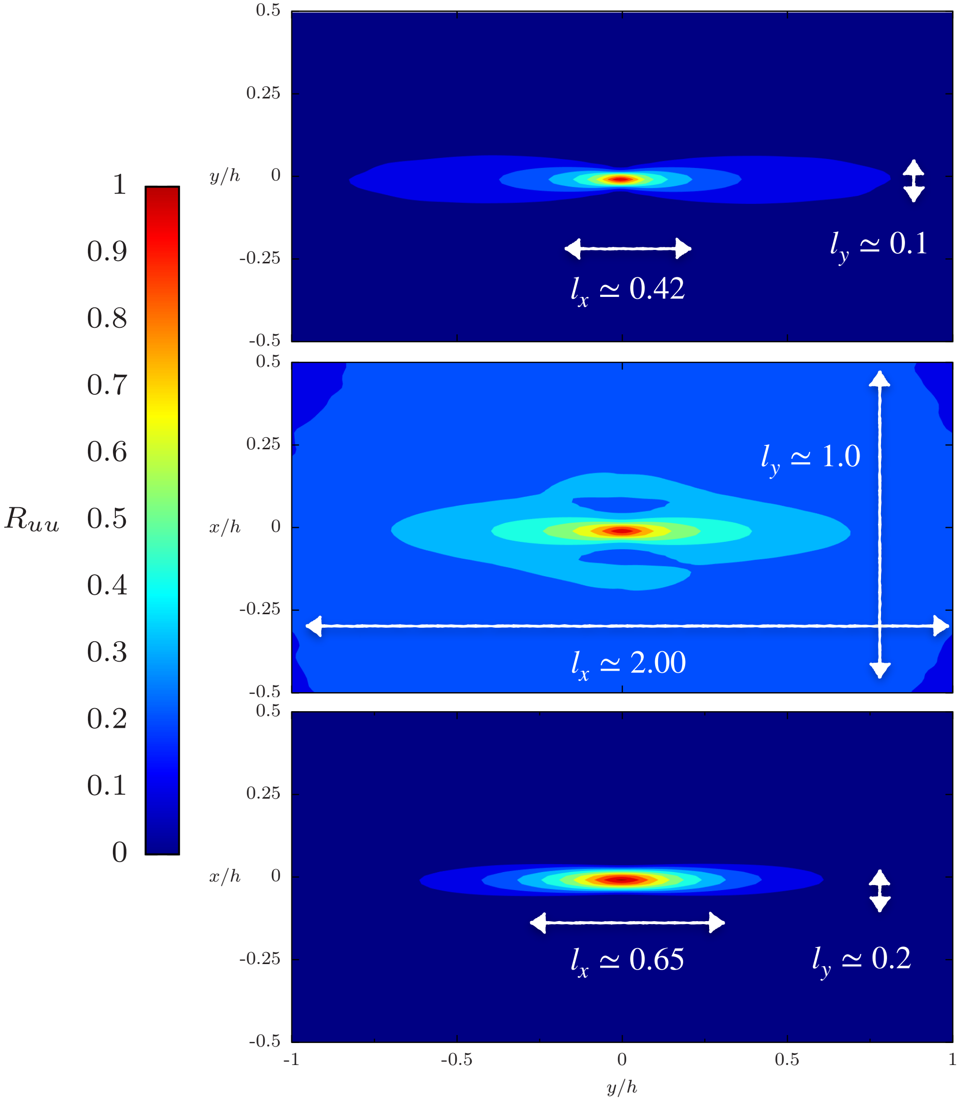
Iso-contour $R_{uu}=0.3$

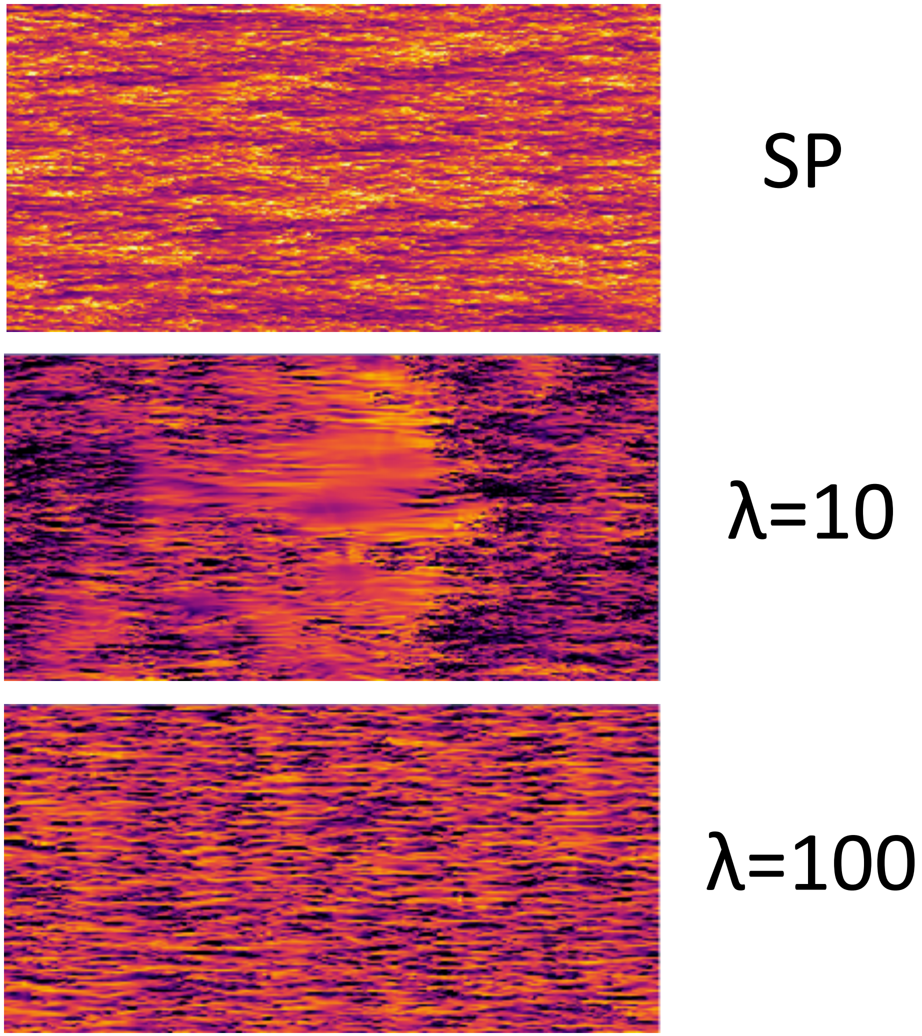
Characteristic spanwise length scale l_y

Characteristic streamwise length scale l_x

Lee & Sung, Comparison of very-large-scale motions of turbulent pipe and boundary layer simulations, PoF (2013)

Stratified cases
Streamwise correlations



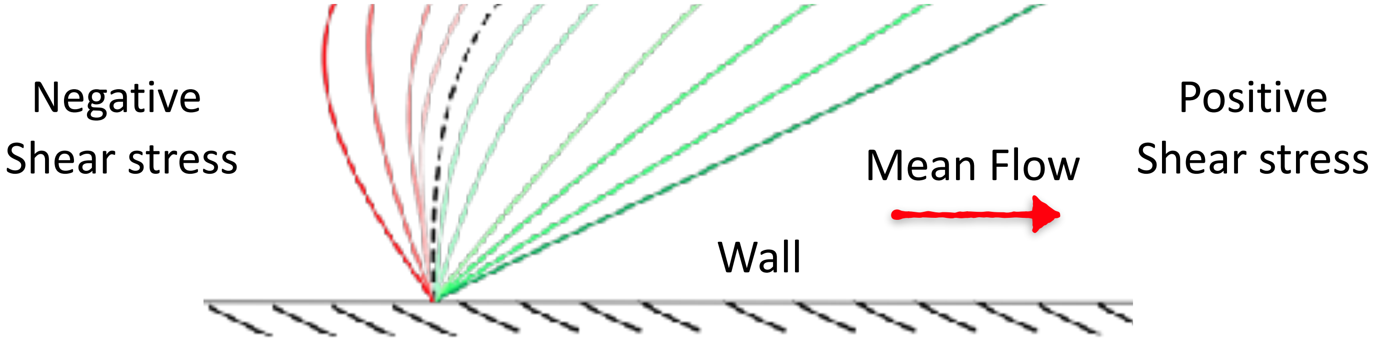


Slice located at z/h=-0.99 (10 w.u. from the wall).

$$\lambda = \frac{\eta_o}{\eta_w} = \frac{\text{Core (oil)}}{\text{Lubricating (water)}}$$

Results
PDF of wall-shear stress (I)

To characterise turbulence activity, we consider the wall-shear stress.



Negative
Shear stress

Mean Flow

Positive
Shear stress

Wall

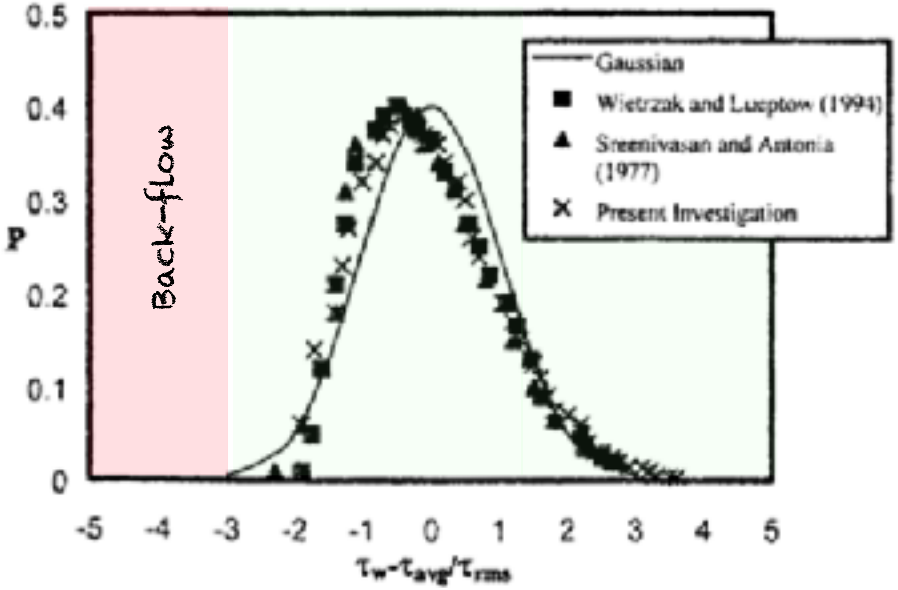
We consider the wall shear stress fluctuations:

$$\tau'_w = \frac{\tau_w - \langle \tau_w \rangle}{\langle \tau_w \rangle}$$

$\tau'_w < -1$ → Back-Flow Event

We compute now this statistics for the stratified cases.

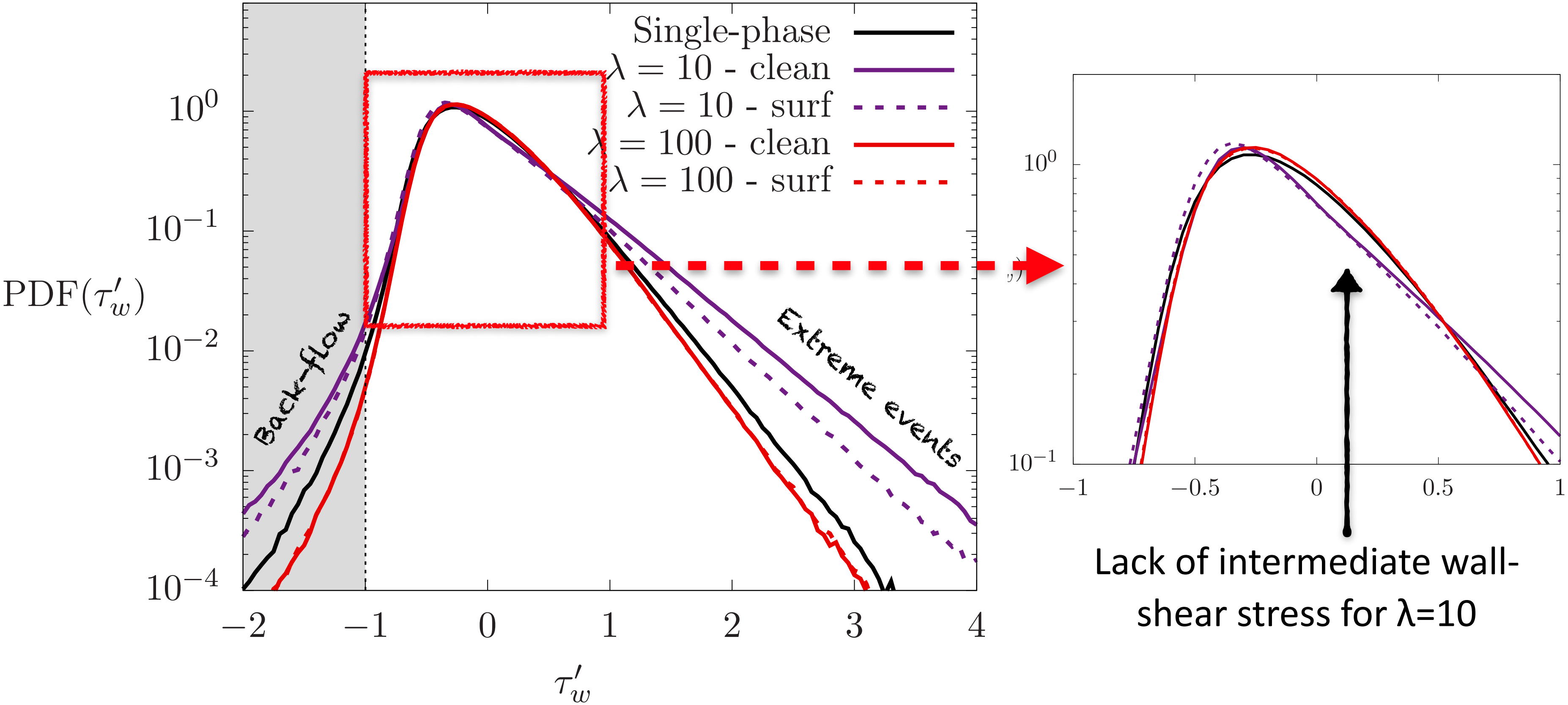
Single-phase flow:



Wietrzak & Lueptow, Wall shear stress and velocity in a turbulent axisymmetric boundary layer, JFM (1994)
Colella & Keith, Measurements and scaling of wall shear stress fluctuations, EF (2003)

Results
PDF of wall-shear stress (II)

PDF of wall-shear stress at the two walls:



Lack of intermediate wall-shear stress for λ=10

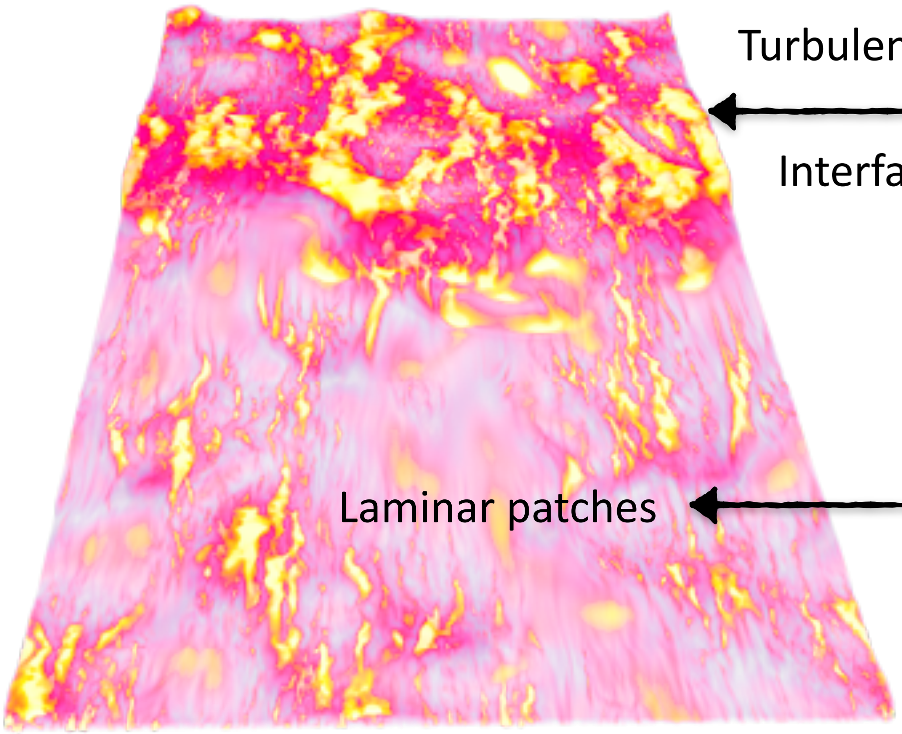
- λ=10 -> Presence of extreme events and lack of intermediate values (intermittent behaviour!)
- λ=100 -> Results are similar to single-phase results (black)
- Surfactant effects is visible only for λ=10

$$\lambda = \frac{\eta_o}{\eta_w} = \frac{\text{Core (oil)}}{\text{Lubricating (water)}}$$

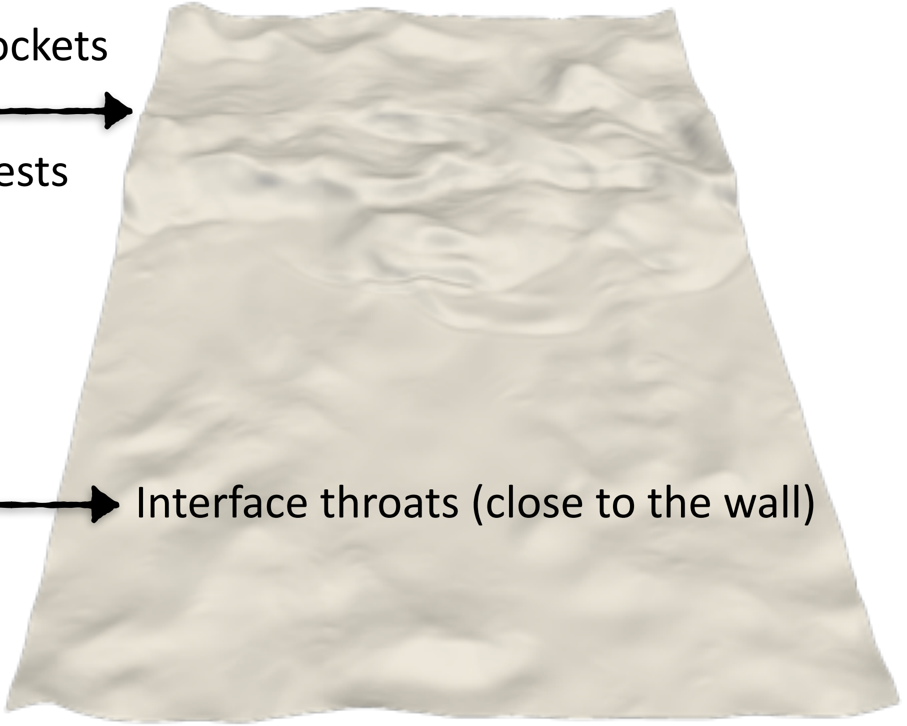
Which is the reason behind this behaviour?

Qualitative view
Interface-Turbulence Interactions (λ=10)

Volume rendering of TKE
(lubricating layer)



Interface position



Turbulence pockets ↔ Interface crests

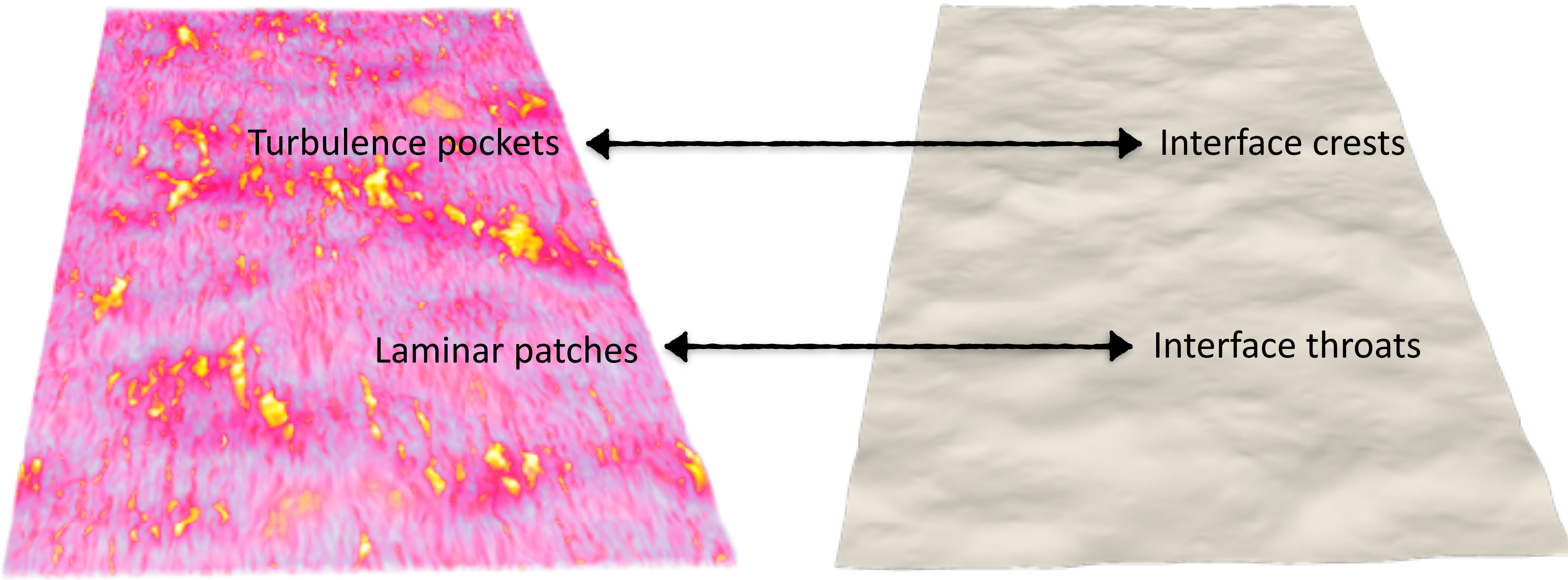
Laminar patches ↔ Interface throats (close to the wall)

Strong interaction between the interface and the turbulence structures in the lubricating layer. Compression of the layer (low thickness) produce laminar patches while expansion of the layer (larger thickness) produce turbulence pockets.

$$\lambda = \frac{\eta_o}{\eta_w} = \frac{\text{Core (oil)}}{\text{Lubricating (water)}}$$

Qualitative view

Interface-Turbulence Interactions (λ=100)



Volume rendering of TKE
(lubricating layer)

Interface position

Turbulence pockets ↔ Interface crests

Laminar patches ↔ Interface throats

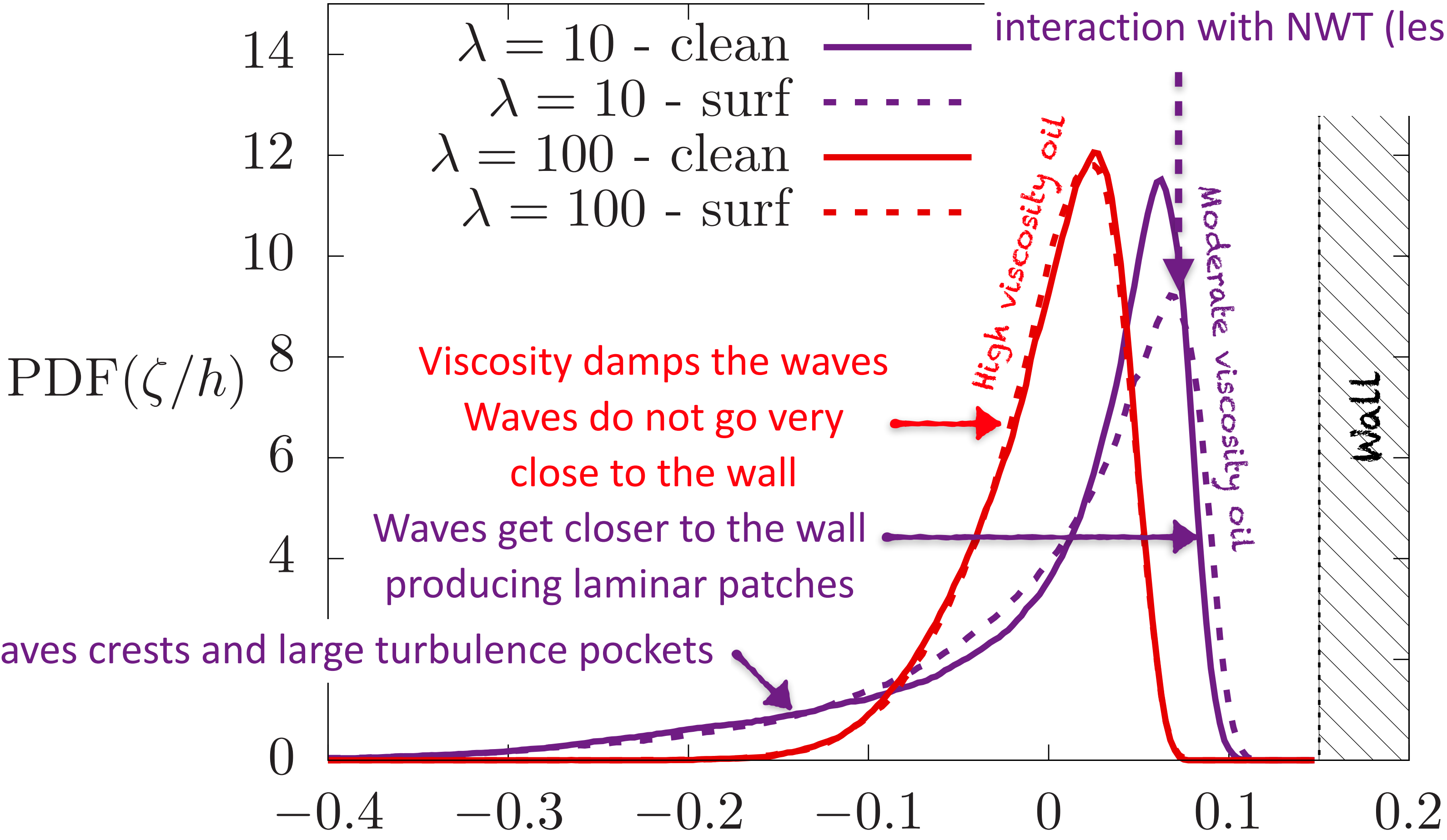
Interaction between interface and turbulence structures is still present.
However, waves and turbulence pockets are more uniformly distributed.
<u>We need to characterise the waves.</u>

$$\lambda = \frac{\eta_o}{\eta_w} = \frac{\text{Core (oil)}}{\text{Lubricating (water)}}$$

Results
PDF of interface elevation

PDF of interface elevation:

Surf-laden case: less interaction with NWT (less DR)



Viscosity damps the waves
Waves do not go very close to the wall

Waves get closer to the wall producing laminar patches

Waves crests and large turbulence pockets

Interface dynamics controls the turbulence behaviour in the lubricating layers..!

Conclusions

- For all viscosity ratios considered, DR is obtained and oil can be transported at the same cost of transporting water. A slightly higher DR is obtained for λ=10.
- For moderate oil viscosity (λ=10), turbulence pockets and laminar patches are observed in the water layer.
- For larger viscosity oil (λ=100), turbulence activity in the layer is rather uniform.
- The interactions between the interfacial waves, oil viscosity and surfactants control the turbulence activity (laminar patches) in the lubricating layer and thus the DR performance.

We acknowledge PRACE for awarding us access to HAWK at GCS@HLRS, Germany.
Prace 2020235507 - wateR lUBrIcated chaNnel (RUBIN) - 101 900 000 core hours.