Universidade de Coimbra

# Numerical Simulation of the Flow of Fiber Suspensions in Pipe with Modified Velocity Profiles

C. Cotas*, F. Garcia, P. Ferreira, P. Faia, D. Asendrych and M.G. Rasteiro

*COST ACTION FP1005*
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1. Objectives
2. Pseudo-homogeneous Approach
3. Modified Velocity Profiles
4. Numerical Results
5. Future Work

# 1. Objectives

**Development of a mathematical model** to describe properly the **flow of fiber suspensions in pipes**

- Modeling of pipe fiber suspensions flow
- Characterization of the pulp fiber rheology
- Adapt the standard *k*-*ε* turbulence model to take into account the presence of fibers
- Validation of the model

# Computational Strategies

**CFD –** Computational Fluid Dynamics

- **Pseudo-homogeneous model**

- **Mass conservation equation** and **equations of motion**

- **Standard *k-ε* turbulence model**

- **Eucalyptus**, **Pine** and **Recycled** fiber suspension

- **Adapt the CFD code** to take into account the presence of fibers in the flow

➢ **ANSYS FLUENT**

# Experimental Results

- **Flow rig**: test section (D=7.62cm, L=4m); magnetic flowmeter; differential pressure meter; temperature control and EIT rings.
- **Main results**: pressure drop, fibers distribution (fiber plug evolution) and velocity profiles.

**Figure 1** - Pilot rig existent in DEQ-FCTUC (adapted from Rasteiro (2011)).

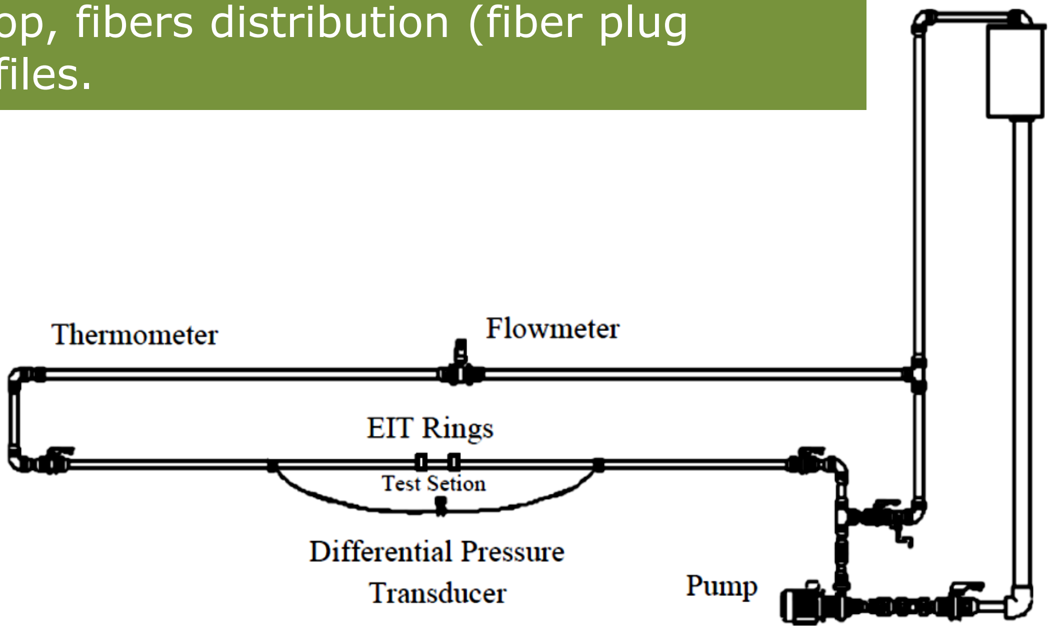



**Figure 2** - Schematic view of the pilot rig existent in DEQ-FCTUC (adapted from Ventura *et al* (2008) and Faia *et al* (2012)).

## Rheological Data

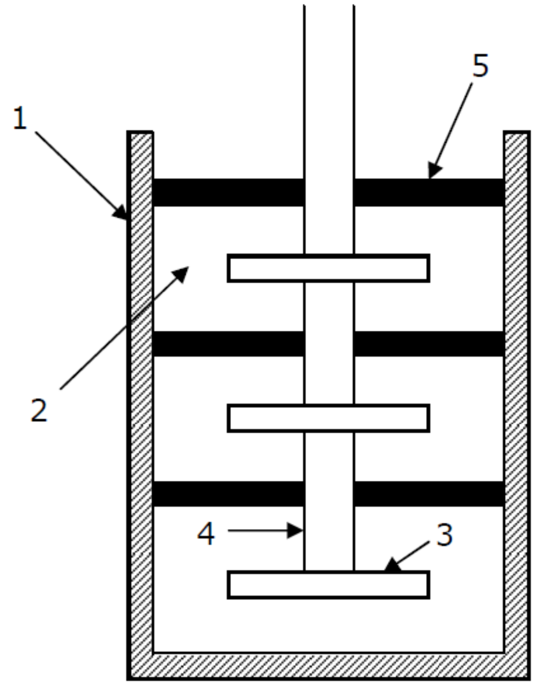
### Apparent viscosity of the pulp fiber suspension

$$\eta_{app} = \frac{\tau}{\dot{\gamma}}$$

$\eta_{app}$ - apparent viscosity

$\tau$ - shear stress

$\dot{\gamma}$ - shear rate




**Legend:**
1 – Vessel
2 – Sample
3 – Moving plate
4 – Rotor
5 – Fixed plate

**Figure 5** - Schematic view of the plate viscometer existent in DEQ-FCTUC (adapted from Blanco *et al* (2007)).

# Rheological Data

## Apparent viscosity of the pulp fiber suspension

$$\eta_{app} = K\left(\dot{\gamma}\right)^{n} \quad (n < 0)$$

$\eta_{app}$ - apparent viscosity

$\dot{\gamma}$ - shear rate

$K$ – consistency coefficient

$n$ – flow behavior index

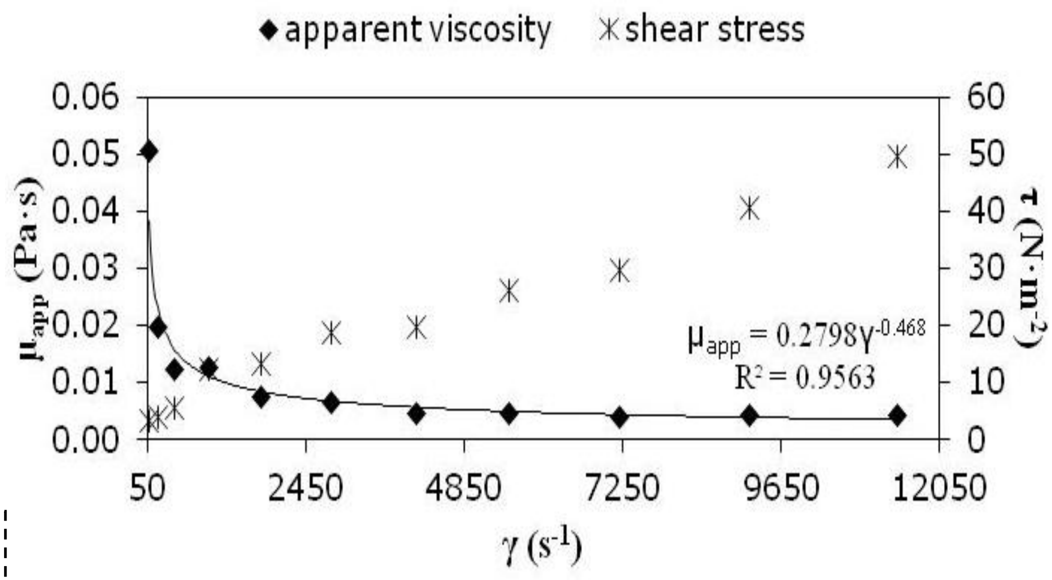



**Figure 6** – Rheogram and apparent viscosity for pulp suspension of eucalyptus fibers (c=1.50%).

# Numerical Conditions

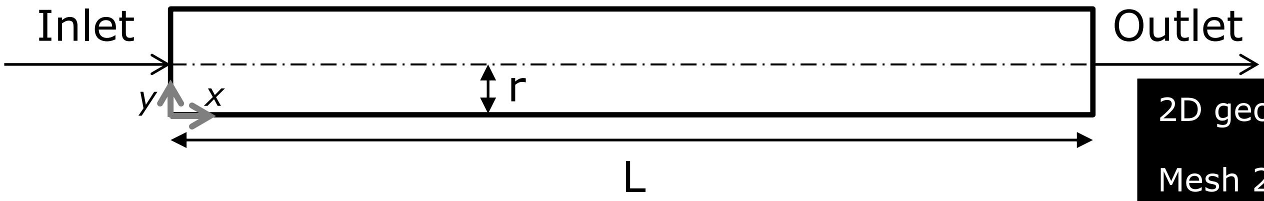



**Figure 7** – Geometry considered.

r = 0.0381 m

L = 1 m

2D geometry

Mesh 20x54 (*x* and *y*)

Convergence criterion = $1 \times 10^{-5}$

| Boundary number | 1 | 3 | 2 | 4 |
|---|---|---|---|---|
| Boundary condition | Periodic boundary condition<br>Inlet mass flow rate, $F_{in}$ | | Axial | Wall |

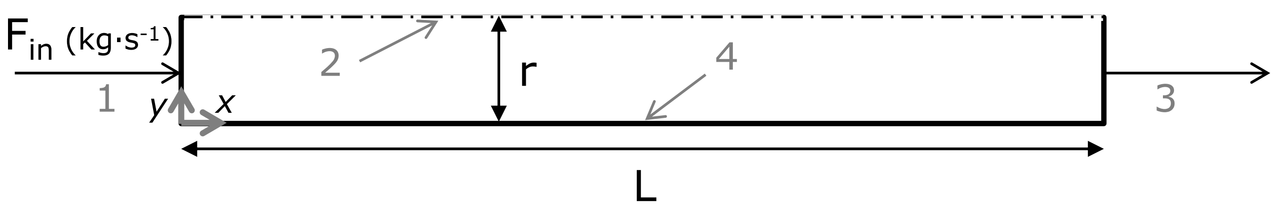



**Figure 8** – Numerical geometry and boundaries.

# Approximation according to Jäsberg (2007)

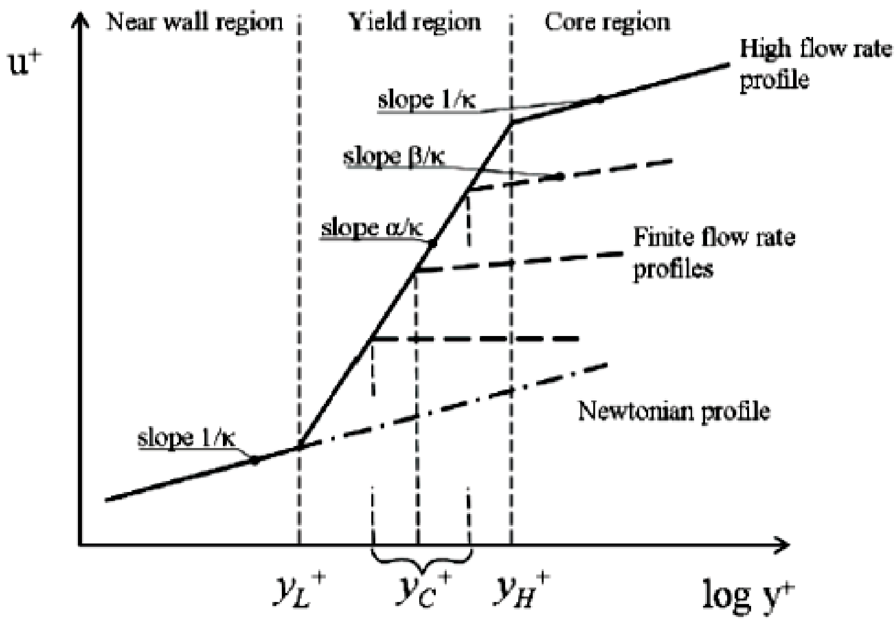



**Figure 9** - Piecewise logarithmic approximation of measured velocity profiles according to Jäsberg (2007).

$y_L^+$ - **dimensionless distance** between the **near wall region** and the **yield region**

$y_C^+$ - position of the **plug surface** (region between the high flow rate envelope curve and the upper limit of the yield region)

$y_H^+$ - **dimensionless distance** between the **yield** and **core region**

$\alpha$ - **indicator of the slope** in relation to Newtonian profile of the envelope curve in the **yield region**

$\beta$ - **indicator of the slope** in relation to Newtonian profile of the envelope curve in **core region**

## Approximation according to Jäsberg (2007)

$$\boxed{u^+ = \frac{1}{k} ln\left(y^+\right) + B + \Delta u^+} \qquad (1)$$

$$\Delta u^+ = \begin{cases} 0, \quad 0 < y^+ \le y_L^+ \\ \frac{\alpha}{k} ln\left(\frac{y^+}{y_L^+}\right), \quad y_L^+ < y^+ \le y_C^+\left(\le y_H^+\right) \\ \Delta u_C^+ - \frac{\beta}{k} ln\left(\frac{y^+}{y_C^+}\right), \quad y_C^+ < y^+ \le R^+ \end{cases} \qquad (2)$$

→ Near wall region

→ Yield region

→ Core region

$$\Delta u_C^+ = \frac{\alpha}{k} ln\left(\frac{y_C^+}{y_L^+}\right) \qquad (3)$$

# Wall law modification and non-Newtonian fluid

## Case study

**Turbulent water flow in pipe**

- $U_{in}$ = 4.21 m·s$^{-1}$ $\Delta P/L_{(literature)}$ = 1675.7 Pa·m$^{-1}$
- $U_{in}$ = 6.21 m·s$^{-1}$ $\Delta P/L_{(literature)}$ = 3419.8 Pa·m$^{-1}$
- $\rho$ = 998.2 kg·m$^{-3}$
- $\mu$ = 1.002×10$^{-3}$ Pa·s

**Eucalyptus fiber suspension flow in pipe**

- $U_{in}$ = 4.21 m·s$^{-1}$ $\Delta P/L_{(experimental)}$ = 788.7 Pa·m$^{-1}$
- $U_{in}$ = 6.21 m·s$^{-1}$ $\Delta P/L_{(experimental)}$ = 1288.7 Pa·m$^{-1}$
- c = 1.50 %(w/w)
- Fiber length = 0.706 mm
- $\rho$ = 998.2 kg·m$^{-3}$
- $\mu = \begin{cases} 1.003\times10^{-3} & \text{water annulus} \\ 0.2798\cdot\dot{\gamma}^{-0.468} & \text{plug region} \end{cases}$

**Table 1** – Parameters for 1% Pine and 2% Birch fiber suspensions (**Jäsberg 2007**).

| Parameter | Pine 1% | Birch 2% |
|---|---|---|
| $y_L^+$ | 120 | 50 |
| $y_H^+$ | 880 | 320 |
| $\alpha$ | 1.8 | 2.4 |
| $u_C^*$ [m·s$^{-1}$] | 0.0047 | 0.0125 |

# Wall law modification and non-Newtonian fluid

**Table 2** – Pressure drop values – viscosity equal to **water viscosity**.

| Case | α | β | $y_L^+$ | $y_C^+$ | $\Delta P/L_{literature}$ ($Pa \cdot m^{-1}$) | $\Delta P/L_{numerical}$ ($Pa \cdot m^{-1}$) |
|---|---|---|---|---|---|---|
| $U_{in} = 4.21\ m \cdot s^{-1}$ | | | | | | |
| 1 | 2.4 | 0 | 50 | 320 | 1675.7 | 1114.4 |
| 2 | 4.4 | 0 | 100 | 320 | | 1616.1 |
| 3 | 2.4 | 0 | 50 | 320 | 1675.7 | 1114.4 |
| 4 | 4.4 | 0.5 | 100 | 320 | | 1616.2 |
| $U_{in} = 6.21\ m \cdot s^{-1}$ | | | | | | |
| 5 | 2.4 | 0 | 50 | 320 | 3419.8 | 2042.0 |
| 6 | 4.4 | 0 | 100 | 320 | | 3393.0 |
| 7 | 2.4 | 0 | 50 | 320 | 3419.8 | 2042.0 |
| 8 | 4.4 | 0.5 | 100 | 320 | | 3275.8 |

**Table 3** – Pressure drop values – viscosity as a function of **local shear rate** considering a **water annulus**.

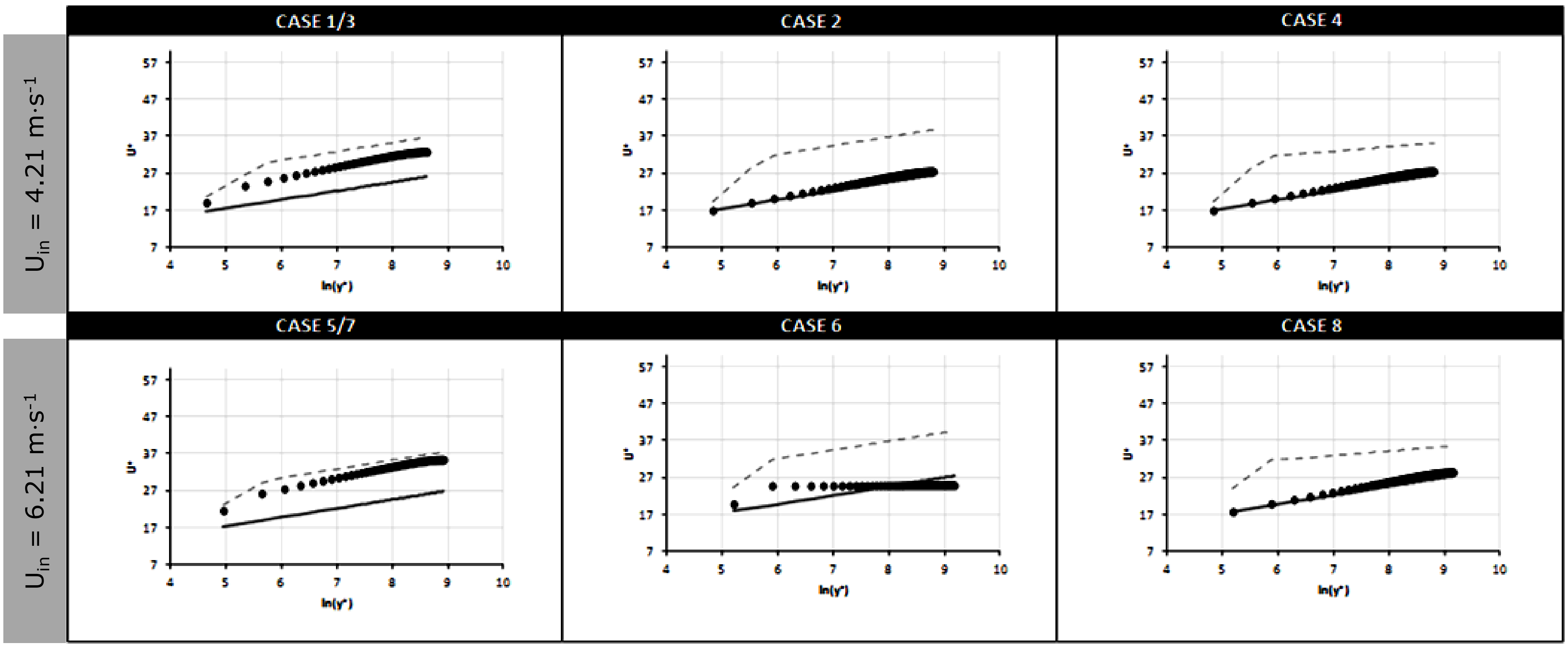
| Case | α | β | $y_L^+$ | $y_C^+$ | $\Delta P/L_{experimental}$ ($Pa \cdot m^{-1}$) | $\Delta P/L_{numerical}$ ($Pa \cdot m^{-1}$) |
|---|---|---|---|---|---|---|
| $U_{in} = 4.21\ m \cdot s^{-1}$ | | | | | | |
| 9 | 2.4 | 0 | 50 | 320 | 788.7 | 1205.5 |
| 10 | 4.4 | 0 | 100 | 320 | | 1740.5 |
| 11 | 2.4 | 0 | 50 | 320 | 788.7 | 1205.5 |
| 12 | 4.4 | 0.5 | 100 | 320 | | 1740.5 |
| $U_{in} = 6.21\ m \cdot s^{-1}$ | | | | | | |
| 13 | 2.4 | 0 | 50 | 320 | 1288.7 | 2146.9 |
| 14 | 4.4 | 0 | 100 | 320 | | 3384.8 |
| 15 | 2.4 | 0 | 50 | 320 | 1288.7 | 2146.9 |
| 16 | 4.4 | 0.5 | 100 | 320 | | 3425.3 |

## Wall law modification and non-Newtonian fluid

- The pressure drop is influenced by the slope in the yield region and the thickness of the near wall region.
- The slope in the core region doesn't influence the numerical results.
- When the mean inlet velocity increases, the numerical pressure drop increases as well.
- In all the cases tested we could reproduce a drag reduction effect.
- The turbulence parameters of Jäsberg for the Birch case are more adequate for the Eucalyptus pipe flow.

# Wall law modification and non-Newtonian fluid

**Table 4** – $U^+$ profiles (Cases 1-8) – viscosity equal to **water viscosity**.



# Wall law modification and non-Newtonian fluid

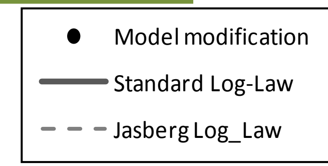
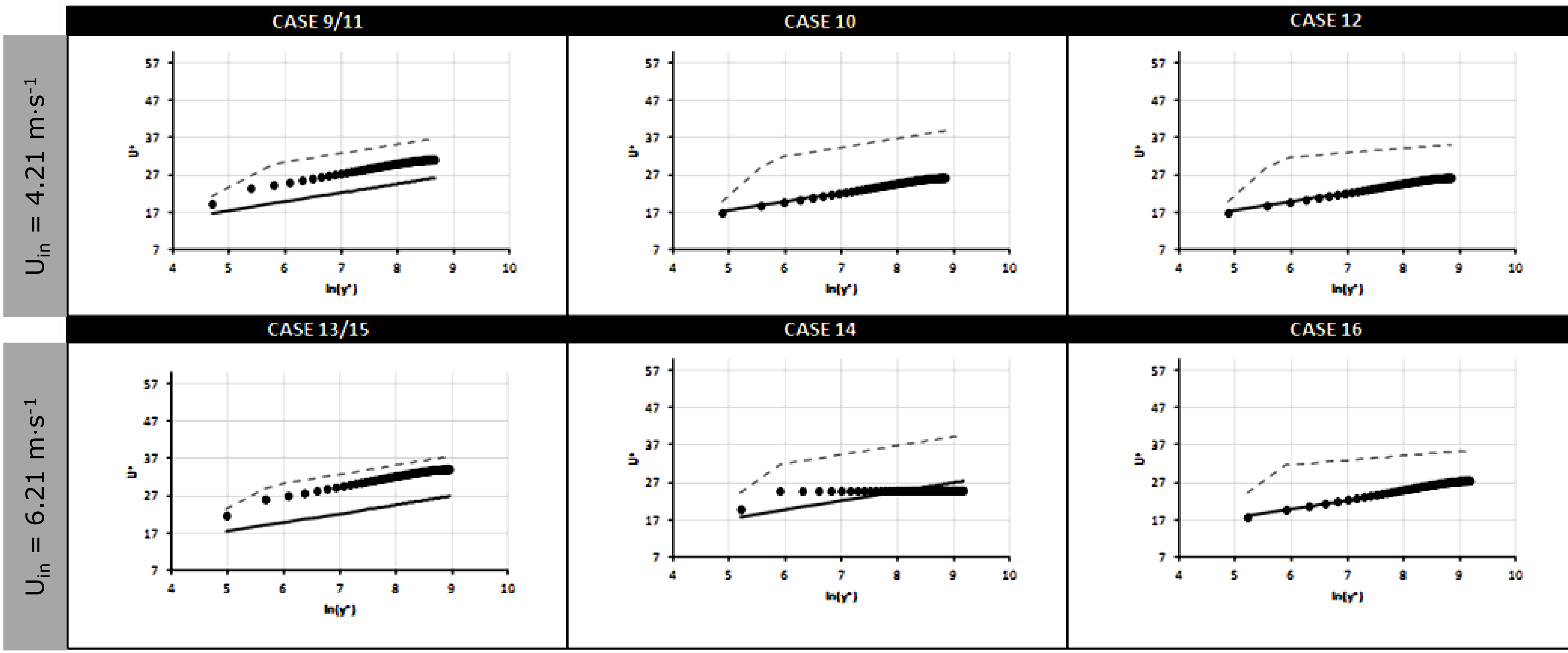



**Table 5** – $U^+$ profiles (Cases 9-16) – viscosity as a function of **local shear rate** considering a **water annulus**.



# Wall law modification and non-Newtonian fluid

## Residuals

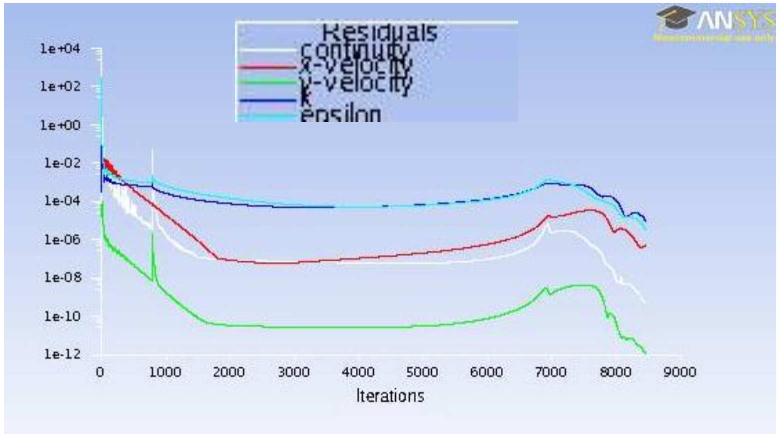



**Figure 10** – Residuals for the **case 1/3** – viscosity equal to **water viscosity**.

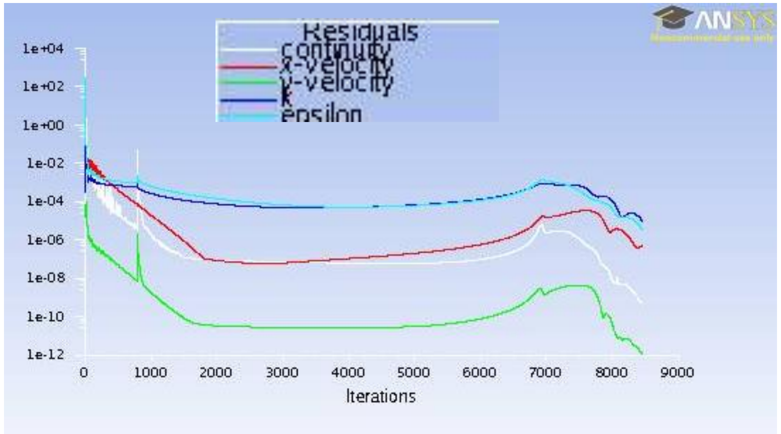



**Figure 11** – Residuals for the **case 9/11** viscosity as a function of **local shear rate** considering a **water annulus**.

# Wall law modification and non-Newtonian fluid

- The $U^+$ profiles are closer to the expected when the turbulence parameters are equal to Jäsberg for the Birch case.
- The increase of the mean inlet velocity leads to a better approximation to the $U^+$ profile expected.
- The modification in the Jäsberg model parameters tested approximates the velocity profile to the Newtonian one.
- When the suspension viscosity is used the maximum velocity decreases, as expected.

- Test further the influence of Jäsberg adjustable parameters on pressure drop and velocity profiles for different fiber suspensions.

- Test a **new expression** to **modify the velocity profiles** based in the studies of Shen and Lin (2010):

$$\boxed{u^+ = \frac{1}{k}\ln\left(y^+\right) + B + w\left(\frac{y}{0.5b}\right) + C} \qquad w\left(\frac{y}{0.5b}\right) = \frac{2\Pi}{k}\sin^2\left(\frac{\pi}{2}\frac{y}{r_0}\frac{1}{0.6}\right)$$

Constants: $C = f(\mathrm{Re}, c, r)$ $\Pi = f(\mathrm{Re}, c, r)$

- Change the turbulence model by the **adjustment of the turbulence parameters** (**turbulence length scale and turbulence intensity scale)** to include the presence of fibers in the flow.

- **Use the CFD model to simulate the pulp flow for different fiber types, flow rates and consistencies**.

# Thank you for your attention...

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$$\Delta u^+ = \begin{cases} 0, \quad 0 < y^+ \le y_I^+ \\ \frac{\alpha}{k} ln\left(\frac{y^+}{y_I^+}\right), \quad y_I^+ < y^+ \le y_C^+ \left(\le y_H^+\right) \\ \Delta u_C^+ - \frac{\beta}{k} ln\left(\frac{y^+}{y_C^+}\right), \quad y_C^+ < y^+ \le R^+ \end{cases} \qquad (2)$$

$$u^+ = \frac{u_p}{\sqrt{\frac{\tau_W}{\rho}}} \qquad y^+ = y\frac{u^*}{\upsilon_f} \qquad u^* = \sqrt{\frac{\tau_W}{\rho_f}} \qquad R^+ = R\frac{u^*}{\upsilon_f}$$

# Non-Newtonian viscosity and water annulus

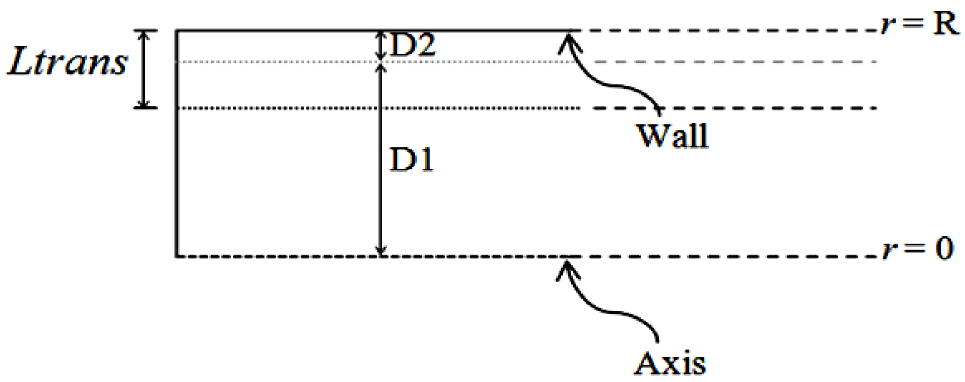


**Figure 12** – Domain tested considering the water annulus and the mesh refinement in a zone near the wall.

$$\mu\begin{cases} 1.003\times10^{-3}, & R-Ltrans < r \le R \\ 0.2798\cdot\dot{\gamma}^{-0.468}, & 0 \le r \le R-Ltrans \end{cases} \qquad (4)$$