RHEOLOGY OF FIBRE SUSPENSIONS:
USING THE RHEOLOGICAL CHARACTERIZATION IN CFD MODELS FOR FIBRE FLOW

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Overview

- Introduction
- Objectives
- Rheological characterization
- CFD model
- Results
- Conclusions

Introduction

Flow properties of pulp suspensions are important for the optimization of most unit operations in pulp and paper making. Therefore, it is necessary to understand the specific hydrodynamic features of fibre suspensions.

The design is usually conservative and therefore equipment is normally oversized.

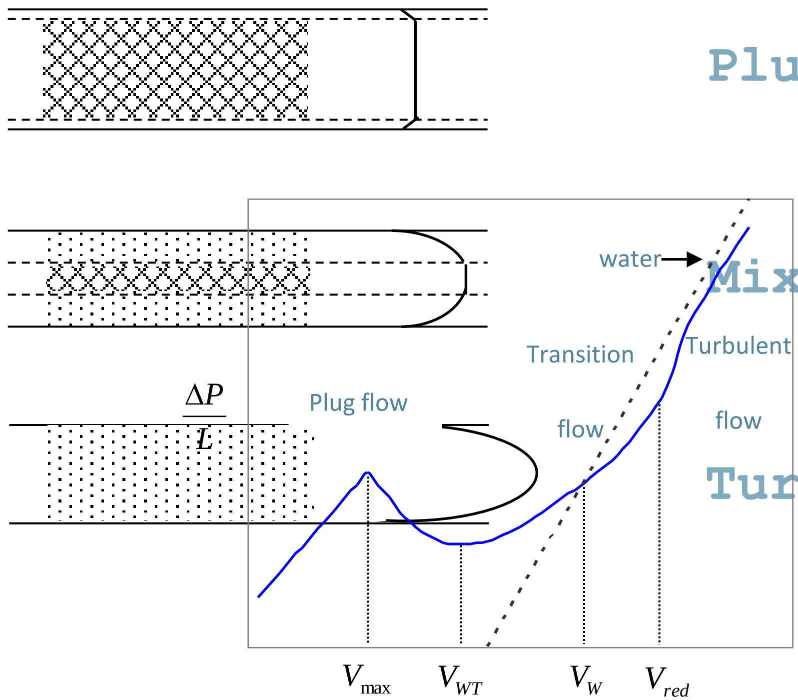
Introduction

Pulp suspensions are different from other solid-liquid systems because of the unique interactions among the different components of the fibre furnish: fibres, fines, fillers, additives, etc.

All interactions are very important in these heterogeneous samples giving rise to complex shear mechanisms that are different from classical slurry systems.

Introduction

Pulp suspensions flowing in pipes exhibit three basic types of shear flow mechanisms:



Plug Flow

Mixed Flow

Turbulent Flow

Objectives

Construction of a flow model able to predict the flow behaviour of pulp fibre suspensions represents an important step in this area.

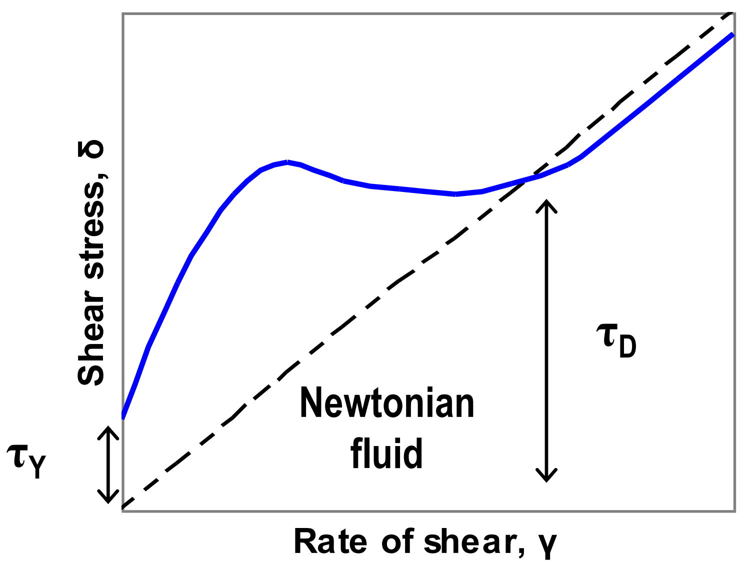
Strategy: Pseudo-Homogeneous Model

Knowledge of the rheological behaviour is essential for the construction of a realistic model.

The $k-\varepsilon$ Turbulence Model is one of the simplest and most used turbulence models for industrial applications.

Rheological characterization

Typical rheogram for a pulp fibre suspension



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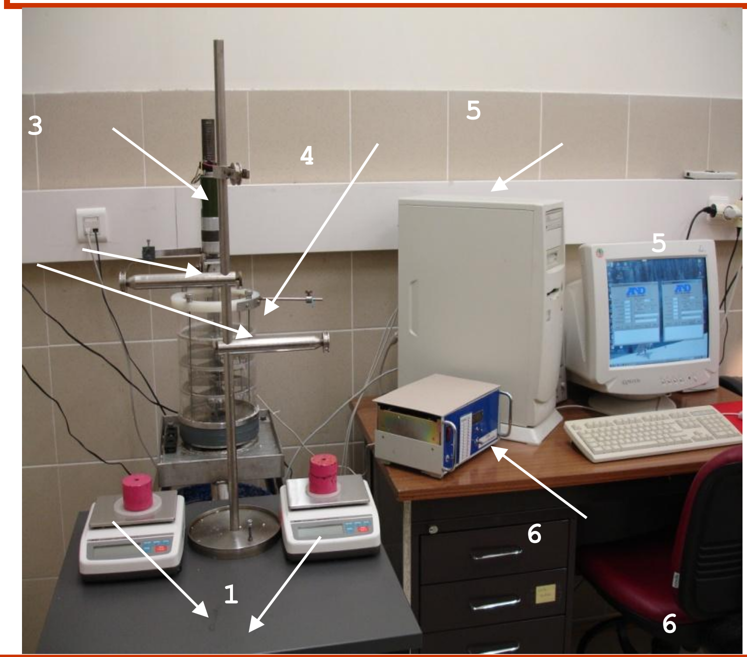
Rheological characterization

New plate rotational Rheometer – Searl effect



1-Analytical scales;
2-Arms to measure torque;
3-Rotor;
4-Vessel;
5-Computer connected to the scales;
6-device to control velocity.

Induces uniform fibre distribution

Measures shear in the rotor (mobile plate) and in the vessel (fixed plate)

Calculates the difference between torque applied by the rotor and torque transmitted by the fluid to the vessel

Rheological characterization

Suspensions tested:

Pulp Type	Fibre length (mm)	Consistencies % (w/w)
Recycled pulp	1.14±0.04	1.4 – 4.23
Eucalypt bleached kraft pulp	0.71±0.03	1.45 – 3.5
Eucalypt (90%) + pine (10%) bleached pulp	0.61±0.06	0.9 – 3.2
Pine unbleached kraft pulp	2.56 ±0.14	0.8 – 3.6

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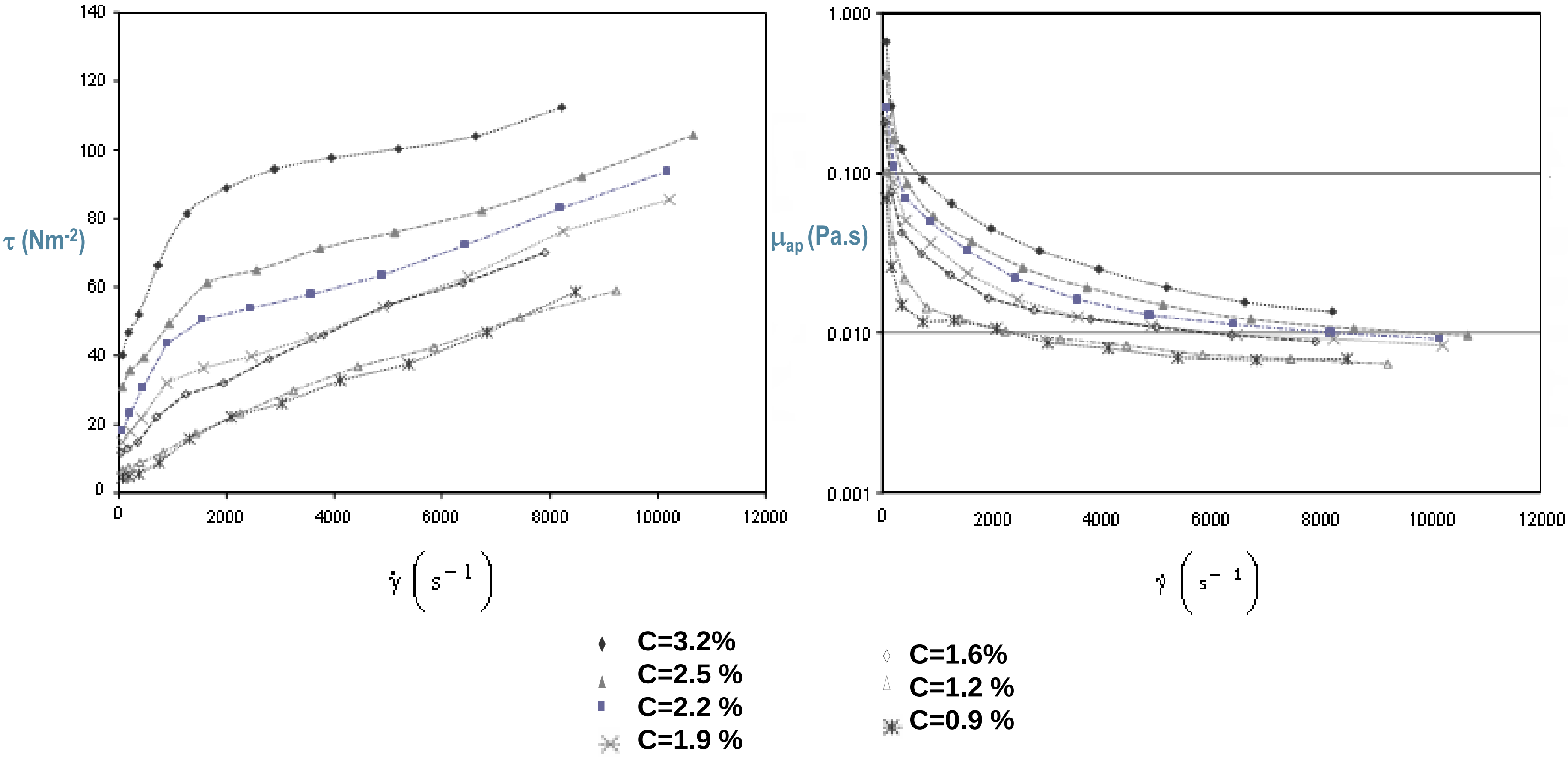
Rheological characterization

Typical Rheograms



pine + eucalyptus suspension

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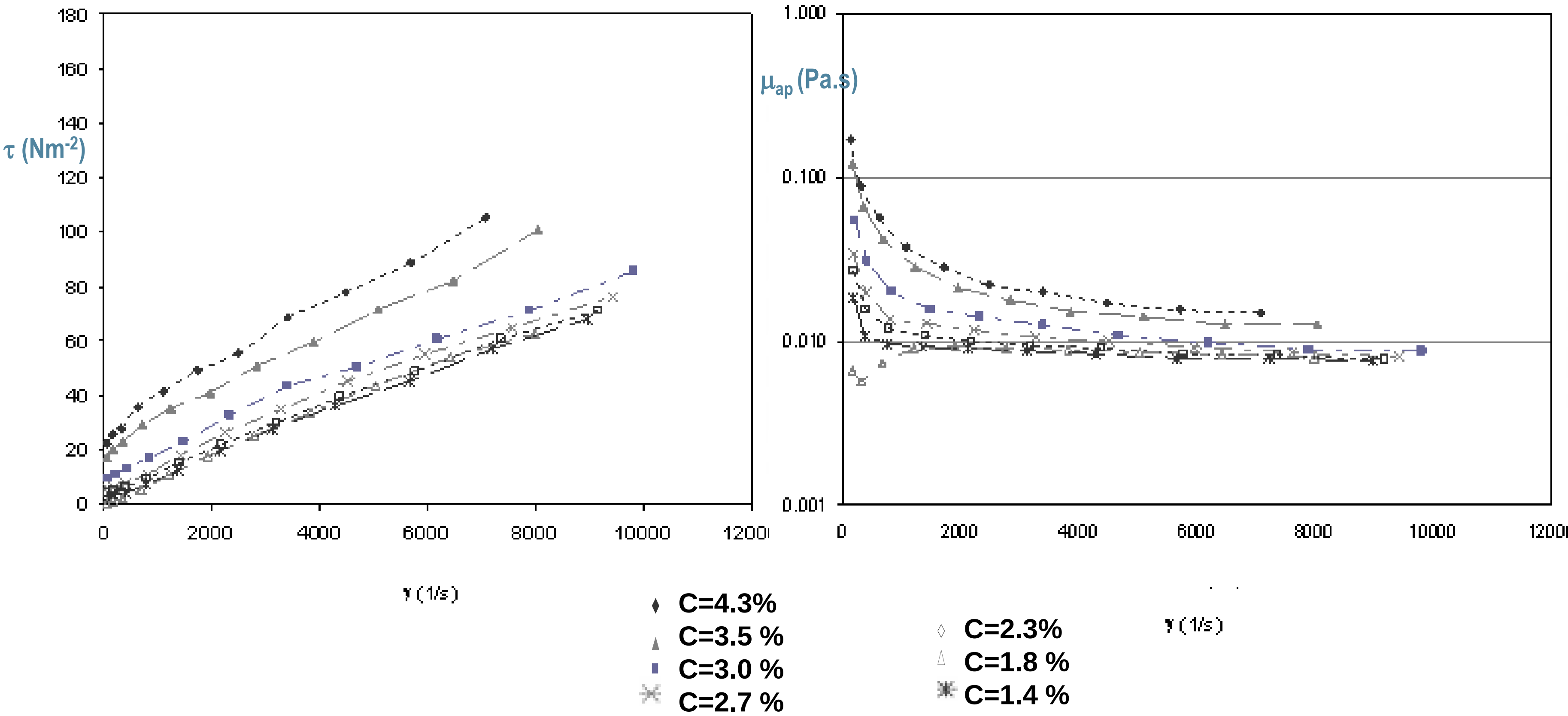
Rheological characterization

Typical Rheograms



Recycled suspension

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Rheological characterization

Herschel-Bulkley model

$$\tau = \tau_y + k(\dot{\gamma})^n$$

τ_y - yield stress

k – consistency coefficient

n – flow index

-Using an experimental design the influence of fibre characteristics (length), consistency and temperature on τ_y were evaluated.

- n an k are mainly influenced by consistency

- Yield stress increases with consistency and fibre length
- Temperature has got a negative effect on yield stress

See: Ventura C, Blanco A, Negro C, Ferreira P, Garcia F, Rasteiro M, Tappi J, 6 (7) 17 (2007)

Flow model

Pseudo-Homogeneous Model

Objective:

To model the turbulent flow of pulp fibre suspensions in pipes using CFD(FEM).

COMSOL Multiphysics Software, version 3.5

Governing Equations

Continuity equation

$$\nabla \cdot u = 0$$

Conservation of momentum

$$\rho \frac{\partial u}{\partial t} + \rho (u \cdot \nabla) u = -\nabla p + \nabla \cdot \eta \left(\nabla u + (\nabla u)^T \right) + F$$

Standard k-ε model

$$\eta_T = \rho \, C_\mu \frac{k^2}{\varepsilon}$$

Transport Equation for k

$$\rho \frac{\partial k}{\partial t} - \nabla \left[\left(\eta + \frac{\eta_T}{\sigma_k} \right) \nabla k \right] + \rho U \cdot \nabla k = \frac{1}{2} \eta_T \left(\nabla U + (\nabla U)^T \right)^2 - \rho \varepsilon$$

Transport Equation for ε

$$\rho \frac{\partial \varepsilon}{\partial t} - \nabla \left[\left(\eta + \frac{\eta_T}{\sigma_\varepsilon} \right) \nabla \varepsilon \right] + \rho U \cdot \nabla \varepsilon = \frac{1}{2} C_{\varepsilon 1} \frac{\varepsilon}{k} \eta_T \left(\nabla U + (\nabla U)^T \right)^2 - \rho \, C_{\varepsilon 2} \frac{\varepsilon^2}{k}$$

model constants:

Constant	C_μ	$C_{\varepsilon 1}$	$C_{\varepsilon 2}$	σ_k	σ_ε
Value	0.09	1.44	1.92	1.0	1.3

Governing Equations

Equation for k

$$k \, \alpha \left(I_T\right)^2$$

Equation for ε

$$\varepsilon \, \alpha \, \frac{k^{3/2}}{L_T}$$

Equations for the turbulence intensity and length scales

$$I_T = I \, \mathrm{Re}_{D_h}^{-1/8}$$

$$L_T = l \, D_h$$

I – turbulence intensity scaling parameter

l – turbulence length scaling parameter

Viscosity was supplied as a function of local shear rate in the pipe cross-section.

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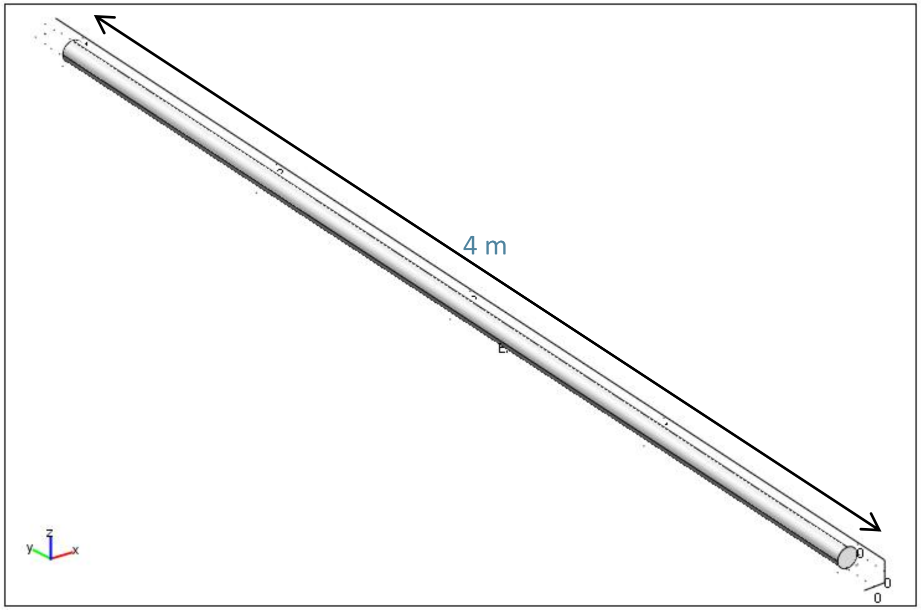
Numerical Implementation

For the CFD modelling the Chemical Engineering module of COMSOL Multiphysics Software version 3.5 was used.

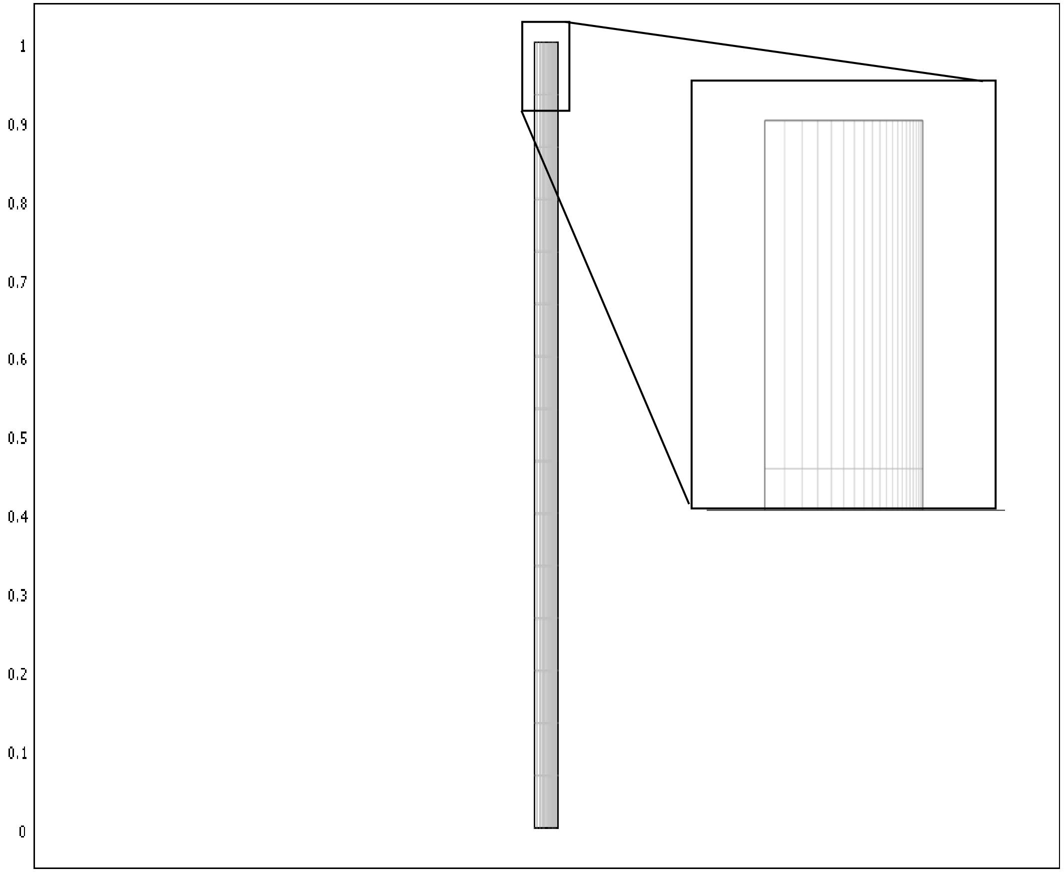
Geometry



The system to be modelled is basically a linear pipe (3 in diameter and 1 m long) where a pulp fibre suspension is flowing.

Numerical Implementation

2D axial symmetry: mesh mode



In order to reach accurate results for the pressure drop, the mesh selected was a mapped mesh consisting of quadrilateral elements.

The mesh is more refined near the wall to resolve the viscous sublayer.

Numerical Implementation

Physics and Boundaries

Inlet Boundary	Plug type cross section velocity profile; The existence of particles, such as fibres, in a fluid flow induces a turbulence damping, thus the L and I values should be smaller then usually assumed for homogeneous fluids Since the turbulent length scale is mentioned to be mainly dependent on the system geometry, it's value was assumed to be constant for all the fibre types and all the consistencies. The intensity scale parameter was adjusted according to the pulp fibre type and concentration.
Outlet Boundary	"Normal Stress, Normal Flow" function
Wall	Logarithm wall function,
Symmetry Boundary	Axial Symmetry

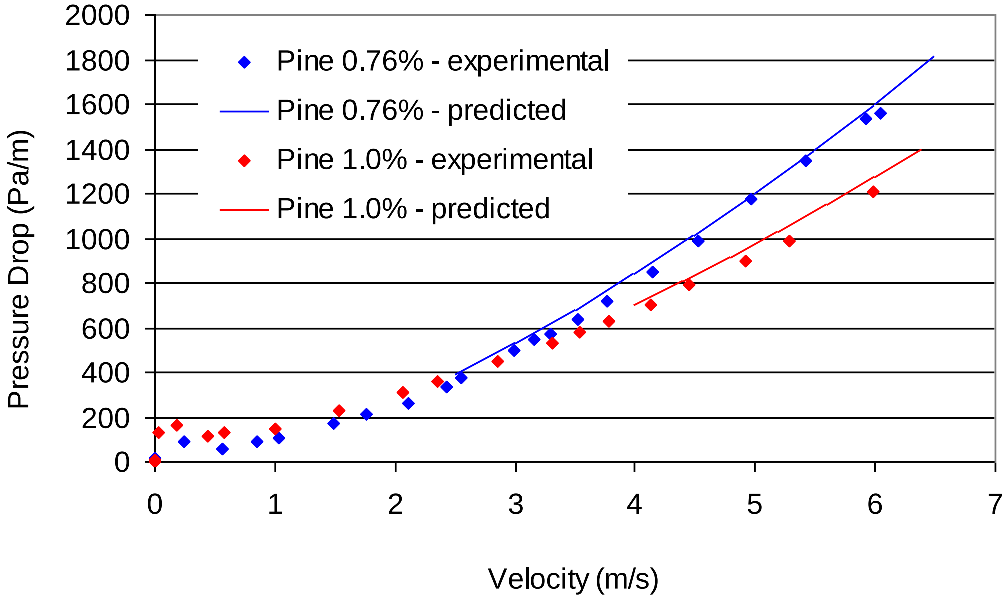
Results

Experimental data

Pulp Type	Consistencies %
	SS Pipes and PE Pipes
	3” and 4”
Recycled pulp	1.4 – 4.23
Eucalypt bleached kraft pulp	1.45 – 3.5
Eucalypt (90%) + pine (10%) bleached pulp	0.9 – 3.2
Pine unbleached kraft pulp	0.8 – 3.6

Results

Comparison with experimental data



$$C = 0.76\% \left| \begin{array}{l} I = 0.01 \\ l = 0.005 \end{array} \right.$$

$$C = 1\% \left| \begin{array}{l} I = 0.0003 \\ l = 0.005 \end{array} \right.$$

Turbulence parameters values

<table>
<tr><th>Pulp type</th><th>Turbulence Parameters</th><th colspan="4">very low consistencies</th><th colspan="6">low consistencies</th></tr>
<tr><td rowspan="3">Recycled</td><td>Consistency (%)</td><td>0.72</td><td colspan="2">0.60</td><td>0.61</td><td>1.40</td><td colspan="2">1.80</td><td colspan="2">2.30</td><td>2.70</td></tr>
<tr><td>I</td><td>0.01</td><td colspan="2">0.01</td><td>0.01</td><td>0.009</td><td colspan="2">0.008</td><td colspan="2">0.007</td><td>0.005</td></tr>
<tr><td>l</td><td>0.005</td><td colspan="2">0.005</td><td>0.005</td><td>0.005</td><td colspan="2">0.005</td><td colspan="2">0.005</td><td>0.005</td></tr>
<tr><td rowspan="3">Eucalypt</td><td>Consistency (%)</td><td colspan="2">0.77</td><td colspan="2">0.91</td><td colspan="3">1.4</td><td colspan="3">1.5</td></tr>
<tr><td>I</td><td colspan="2">0.09</td><td colspan="2">0.09</td><td colspan="3">0.007</td><td colspan="3">0.003</td></tr>
<tr><td>l</td><td colspan="2">0.005</td><td colspan="2">0.005</td><td colspan="3">0.005</td><td colspan="3">0.005</td></tr>
<tr><td rowspan="3">Eucalypt + pine</td><td>Consistency (%)</td><td colspan="2">0.71</td><td colspan="2">0.77</td><td colspan="2">0.9</td><td colspan="2">1.2</td><td colspan="2">1.3</td></tr>
<tr><td>I</td><td colspan="2">0.07</td><td colspan="2">0.05</td><td colspan="2">0.01</td><td colspan="2">0.005</td><td colspan="2">0.003</td></tr>
<tr><td>l</td><td colspan="2">0.005</td><td colspan="2">0.005</td><td colspan="2">0.005</td><td colspan="2">0.005</td><td colspan="2">0.005</td></tr>
<tr><td rowspan="3">Pine</td><td>Consistency (%)</td><td colspan="2">0.66</td><td colspan="2">0.76</td><td colspan="3">0.8</td><td colspan="3">1</td></tr>
<tr><td>I</td><td colspan="2">0.01</td><td colspan="2">0.01</td><td colspan="3">0.0005</td><td colspan="3">0.0003</td></tr>
<tr><td>l</td><td colspan="2">0.005</td><td colspan="2">0.005</td><td colspan="3">0.005</td><td colspan="3">0.005</td></tr>
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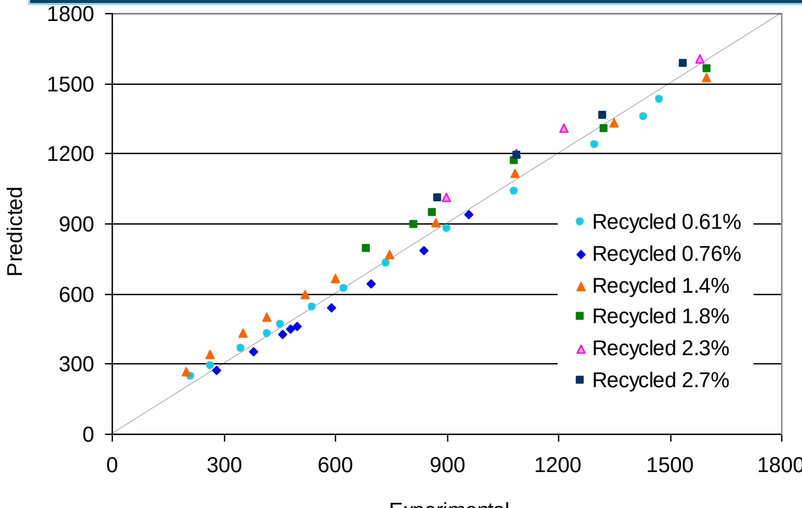
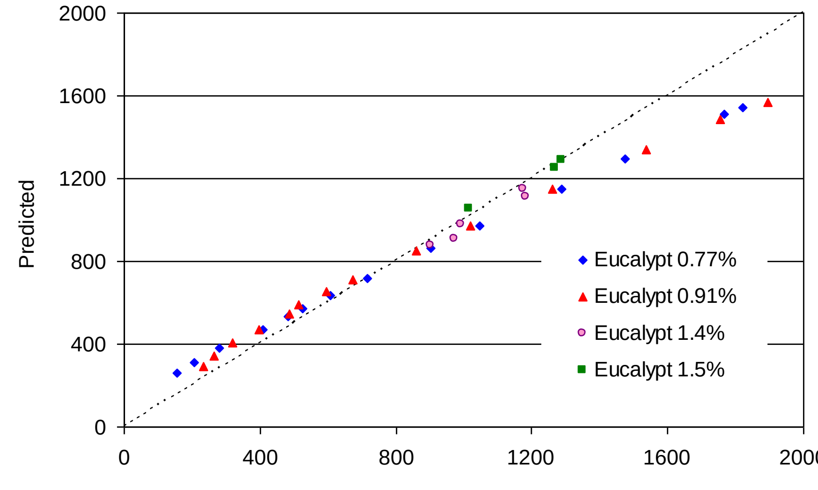
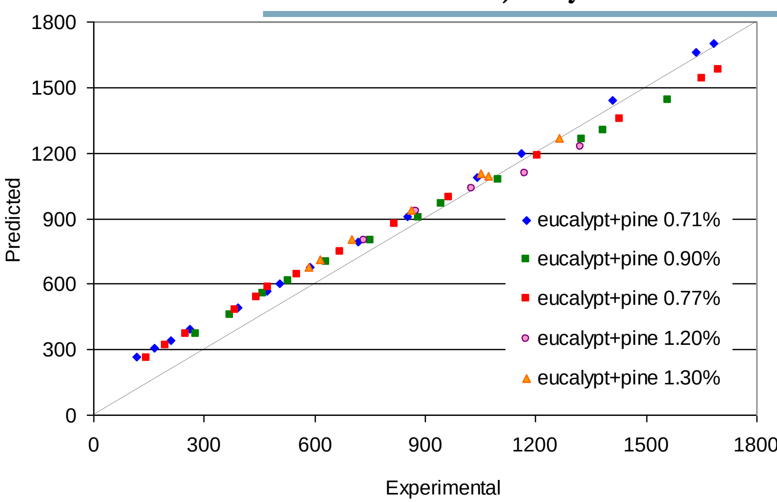
Comparison between predicted and experimental pressure drop (Pa/m) for the turbulent regime



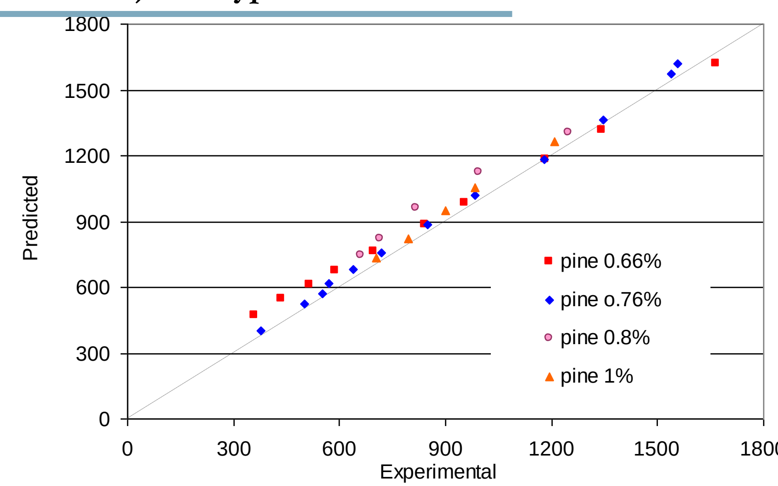
a) recycled



b) eucalypt



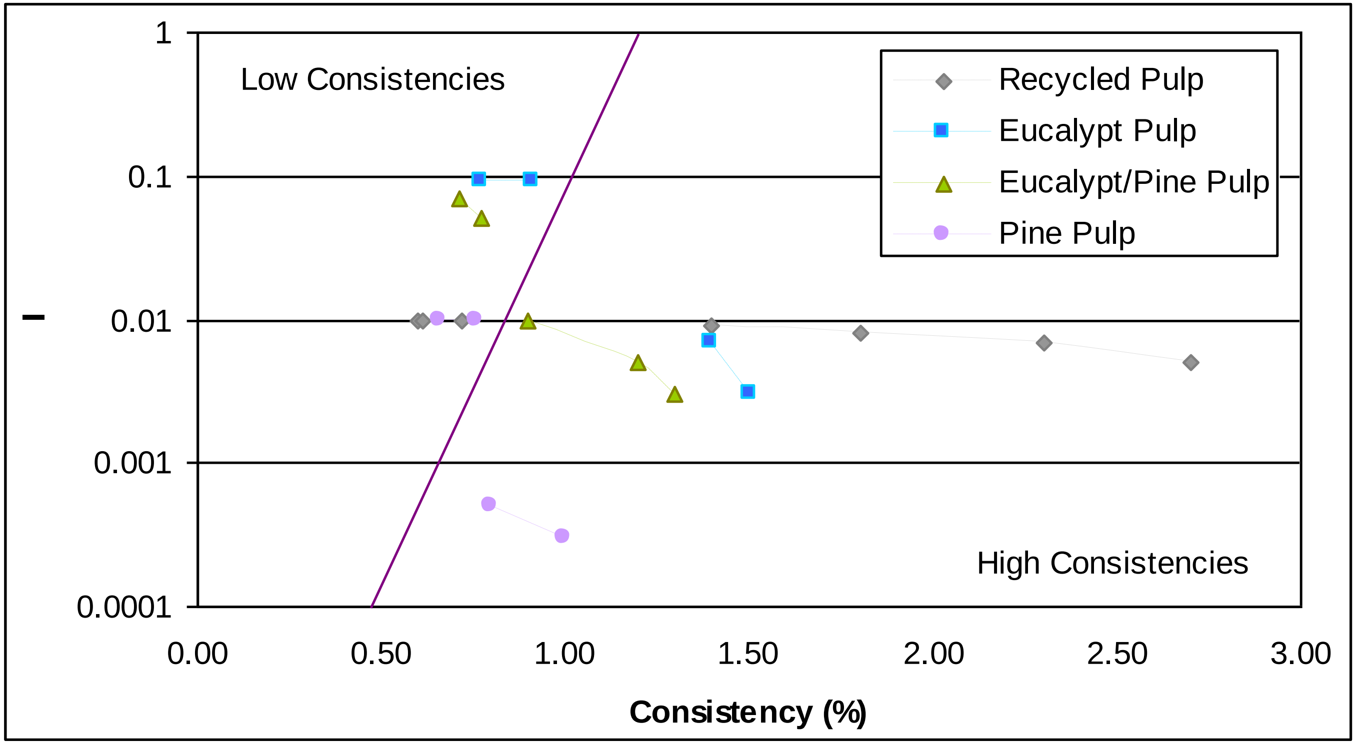
c) eucalypt+pine



d) pine

Results

Turbulence intensity scaling parameter versus suspension consistency



Conclusions

- The pressure drop profiles obtained using COMSOL Multiphysics Software agree very well with the experimental results obtained.
- The use of the k-ε Turbulence Model, associated with the rheological data acquired in a specially built viscometer, revealed to be a good strategy for the prediction of pressure drop values for fibre suspension flow.
- For very low consistencies the I value is minimally influenced by the consistency increase.
- For relatively high values of consistency, as consistency increases, the I values decrease for all the pulps tested. This boundary is dependent on the fibre type.
- The turbulence damping is higher in the case of the pine suspensions (longer and stiffer fibres), being lower for the recycled fibres suspension.
- Future work must enable the establishment of quantitative correlations for the turbulence intensity and length scales, as a function of fibre characteristics and consistency.

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Thank you for your attention

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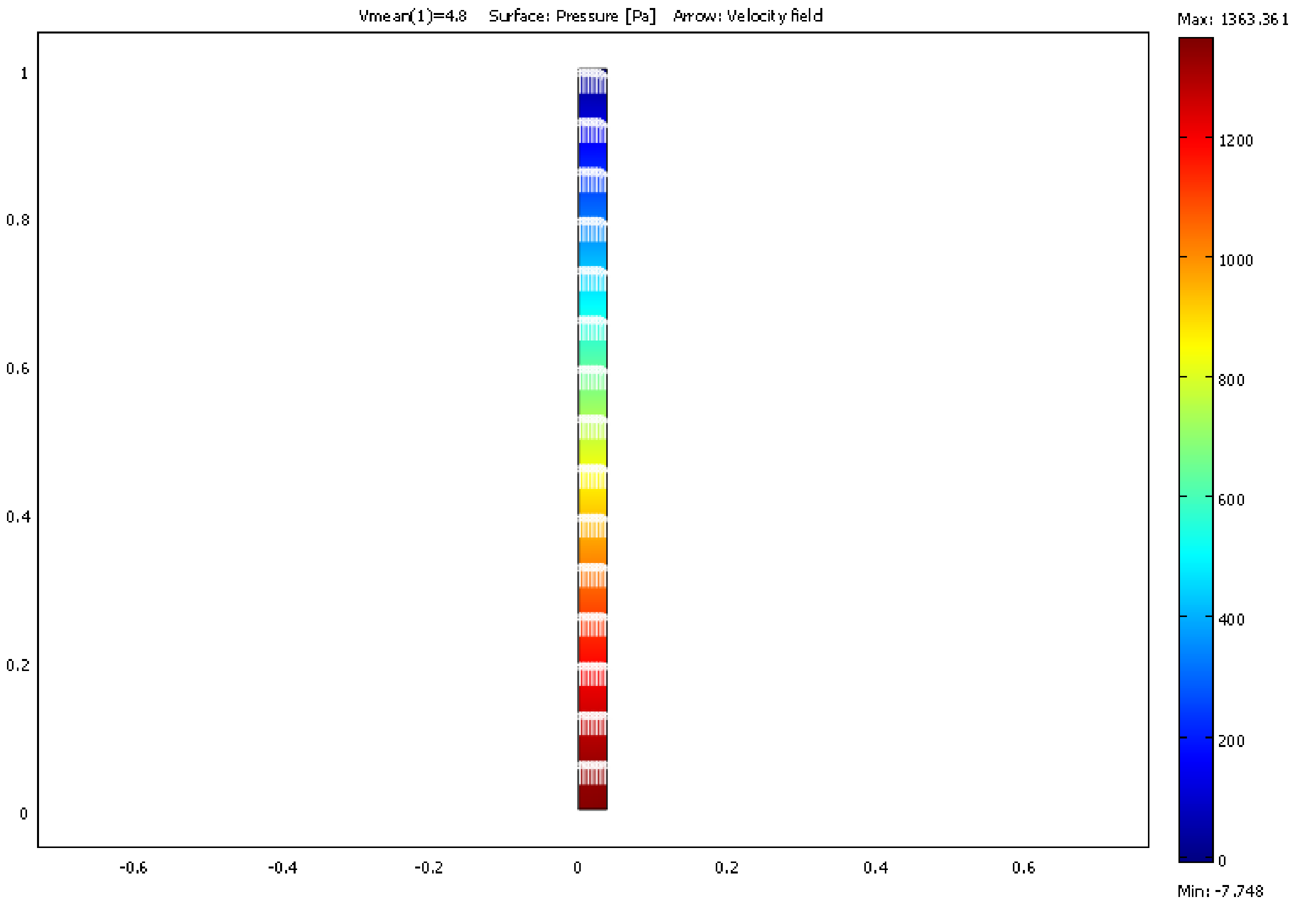
Numerical Implementation

Results and Discussion



Simulated pressure drop for the flow of the recycled pulp suspension with 2.7% (w/w) consistency, at a velocity of 4.8 m/s.

First, the numerical implementation was validated with water. Then, the pulp's physical characteristics were introduced in the model.

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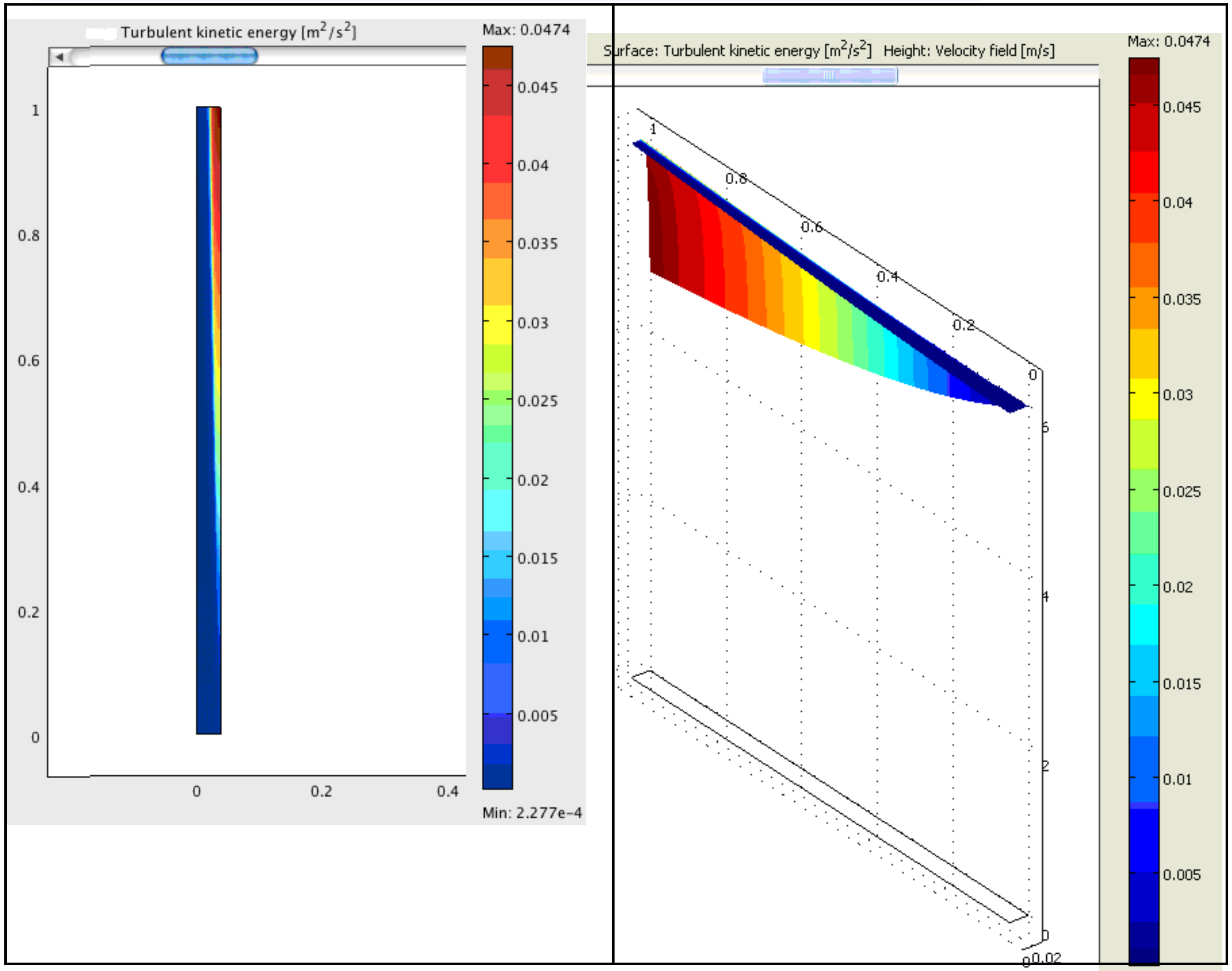
Numerical Implementation

Results and Discussion



Kinetic energy profile for the recycled fibre suspension

0.72% consistency

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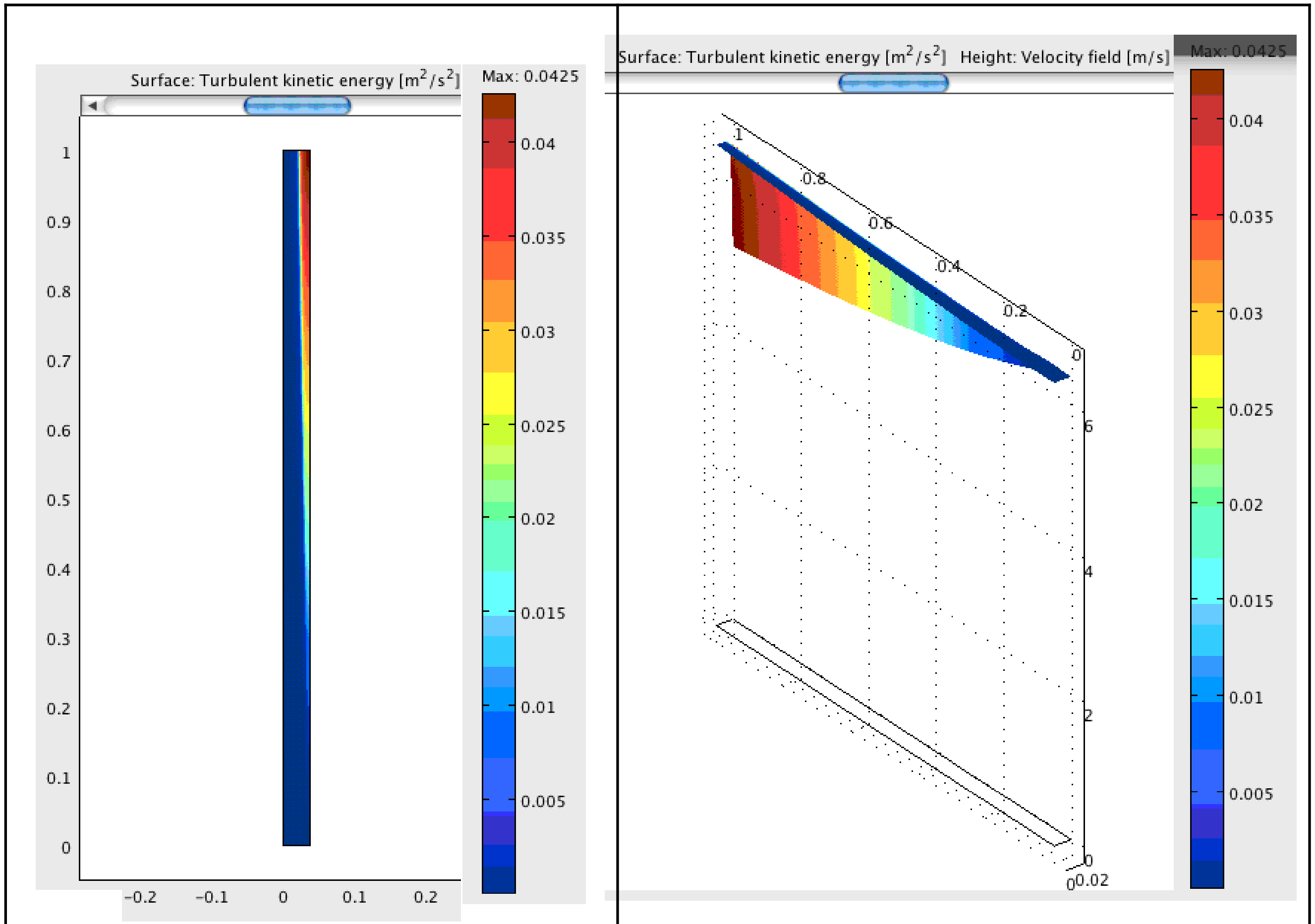
Numerical Implementation

Results and Discussion



Kinetic energy profile for the recycled fibre suspension

2.7% consistency