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CFD simulation of the turbulent flow of pulp fibre suspensions

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Abstract:

Pulp fibre suspensions are complex solid-liquid systems, since their components (fibre, flocs, additives…) present singular and complex interactions between them. As a consequence of this complexity, the understanding of the suspensions flow dynamics remains poor and incomplete, what usually leads to a conservative industrial equipment design and, hence, equipment oversizing.

The purpose of this study is to obtain further knowledge about the dynamic mechanisms of the turbulent flow regime of industrial pulp suspensions, by producing and testing the viability of a model for the turbulent flow of fibre suspensions in conveying pipes, based on fundamental principles of conservation, and also on some experimental information (namely the rheological information) to adjust, empirically, unknown parameters as the fluid viscosity.

With this purpose a numerical model was developed, based on a CFD code, using the Chemical Engineering module of COMSOL Multiphysics Software version 3.4. The $K-\varepsilon$ Turbulence Model was chosen to simulate the pulp suspensions flow. Additionally, the final model was tested and validated using four different industrial pulp suspensions, which were previously fully studied experimentally (flow and rheological tests).

The obtained results demonstrated that the pressure drop profiles obtained using COMSOL Multiphysics Software, for the turbulent flow regime, agree very well with the experimental results obtained in a pilot rig. Additionally, the use of the $k-\varepsilon$ Turbulence Model for the simulation of pulp fibre suspensions flow, associated with the rheological data acquired experimentally, revealed to be a prompt and accurate strategy to attain good prediction of pressure drop values for fibre suspensions flow.

Moreover, the adjustment of the turbulence parameters confirmed previous studies' results, where it was concluded that the existence of particles, such as fibres, in a fluid flow, induces a turbulence damping.

Keywords:
Pulp fibre flow, CFD simulation, turbulence, K-ε model, COMSOL Multiphysics.

1. Introduction

It is known that, contrarily to what happens in the usual suspension systems, the components of the pulp fibre suspensions (fibres, fines, …) are able to develop new "suspension structures" (floccettes, flocs and networks), which modify the suspension nature and consequently the fluid mechanics characteristics.

The flow mechanisms of pulp fibre suspension in pipes have been divided in three different regimes; each regime can be further separated into sub-regimes with well defined shear mechanisms, as can be seen in Figure 1, where pressure drop $\left(\Delta P/_{L}\right)$ is plotted against velocity [1]:

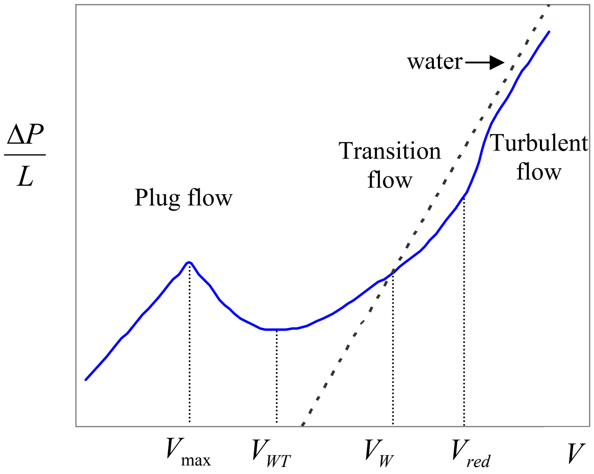


Figure 1 – Pressure drop curve (adapted from [2-6]).

At low velocities the suspension flows as a plug of fibres and water, and the entire shear occurs in a thin layer adjacent to the pipe wall. This induces larger values for pressure drop in pipes than those of water. At intermediate velocities, there is a transition regime where a central and intact plug is surrounded by a turbulent fibre-water annulus. This regime is termed as the transition flow regime, and it starts at the onset of the drag reduction effect, corresponding to a velocity V_W. At high velocities, all the suspension components are in complex turbulent motion, and the pressure drop values are now smaller than the ones expected for water [2-6].

The construction of a flow model able to predict the flow behaviour of pulp fibre suspensions represents an important step in this area, since the numerical modelling can reduce the costs of experiments and prototype equipment usually required to design conveying systems.

The intention of this work is not only to model the turbulent flow of pulp fibre suspensions in pipes, by the use of a finite elements method (FEM) considering a computational fluid dynamics code (CFD), but also to compare the obtained pressure drop results with experimental data.

The $k-\varepsilon$ Turbulence Model is one of the simplest and most used turbulence models for industrial applications, and it was the selected model in this research. Despite of its large application, this model is based on some restrictions, the most important of which are that the Reynolds number is high enough and that turbulence is uniform within boundary layers, which means that production equals dissipation [7]. These assumptions limit the model's accuracy, since they are not always completely correct.

In the present work the suspension is described as a pseudo-homogeneous one phase fluid, which means that the model does not account either for the existence of particles/fibre structures, or for the consistency variation in the flow field. However, it is believed that this restriction does not affect the model's robustness, since for the regime to be modelled all the suspension components are in complete turbulent motion.

This work describes the CFD modelling strategy adopted, making use of the Chemical Engineering module of COMSOL Multiphysics Software version 3.4.

2. Governing Equations

The $k-\varepsilon$ Model is fundamentally based on the Navier-Stokes equations, presented bellow, considering that the fluid is incompressible (ρ=constant) [7-8]:

Continuity equation – represents the conservation of mass:

$$\nabla \cdot u = 0 \tag{1}$$

Vector equation – represents the conservation of momentum:

$$\rho \frac{\partial u}{\partial t} + \rho(u \cdot \nabla)u = -\nabla p + \nabla \cdot \eta\left(\nabla u + (\nabla u)^T\right) + F \tag{2}$$

Energy equation – represents the conservation of energy:

$$\rho\, C_p\left(\frac{\partial T}{\partial t} + (u \cdot \nabla)\, T\right) = -(\nabla \cdot q) + \tau : S - \frac{T}{\rho} \frac{\partial \rho}{\partial T}\bigg|_p \left(\frac{\partial p}{\partial t} + (u \cdot \nabla) p\right) + Q \tag{3}$$

where u is the velocity vector (*m.s*$^{-1}$), ρ is the density (*kg.m*$^{-3}$), p is pressure (Pa), τ is the viscous stress tensor (Pa), F is the body force vector (*N.m*$^{-3}$), C_p is the specific heat capacity at a constant pressure (*J.kg*$^{-1}$*.K*$^{-1}$), T is absolute temperature (K), q is the heat flux vector (*W.m*$^{-2}$), Q contains the heat sources (*W.m*$^{-3}$) and S is the strain rate tensor: $S = \frac{1}{2}\left(\nabla u + (\nabla u)^T\right)$.

The $k-\varepsilon$ Turbulence Model, which is extended to non-Newtonian fluids by allowing the dynamic viscosity to be a function of the velocity field, introduces two additional transport equations and two dependent variables: the turbulence kinetic energy, k, and the turbulence dissipation rate, ε. Turbulent viscosity is modelled by:

$$\eta_T = \rho\, C_\mu \frac{k^2}{\varepsilon} \tag{4}$$

where C_μ is a model constant.

The transport equation for k can be described by analogy with the equations for Reynolds stresses:

$$\rho \frac{\partial k}{\partial t} - \nabla\left[\left(\eta + \frac{\eta_T}{\sigma_k}\right)\nabla k\right] + \rho U \cdot \nabla k = \frac{1}{2}\eta_T\left(\nabla U + (\nabla U)^T\right)^2 - \rho\varepsilon \tag{5}$$

An equation for ε can be derived in a similar manner. Such equation is, however, impossible to model on a term-by-term basis. Instead, all the terms that do not have an equivalent term in the k equation are discarded.

$$\rho \frac{\partial \varepsilon}{\partial t} - \nabla\left[\left(\eta + \frac{\eta_T}{\sigma_\varepsilon}\right)\nabla \varepsilon\right] + \rho U \cdot \nabla \varepsilon = \frac{1}{2} C_{\varepsilon 1} \frac{\varepsilon}{k} \eta_T \left(\nabla U + (\nabla U)^T\right)^2 - \rho\, C_{\varepsilon 2} \frac{\varepsilon^2}{k} \tag{6}$$

The model constants in the aforementioned equations are empirical, and their values can be seen in Table 1.

Table 1 – Model Constants**[7-8]**.

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

3. Numerical Implementation

A system with the characteristics described in the following section has been implemented.

3.1 Real System

The system to be modelled is basically a linear pipe, wherein a pulp fibre suspension is flowing. Experimental pressure drop trials with four industrial types of pulp fibre suspensions (recycled pulp, eucalypt bleached kraft pulp, pine unbleached kraft pulp and eucalypt (90%) + pine (10%) bleached kraft pulp) were previously performed in a pipe 4 m long and with 3 in of diameter. This is the geometry to model, so that a comparison of experimental versus predicted values can be made.

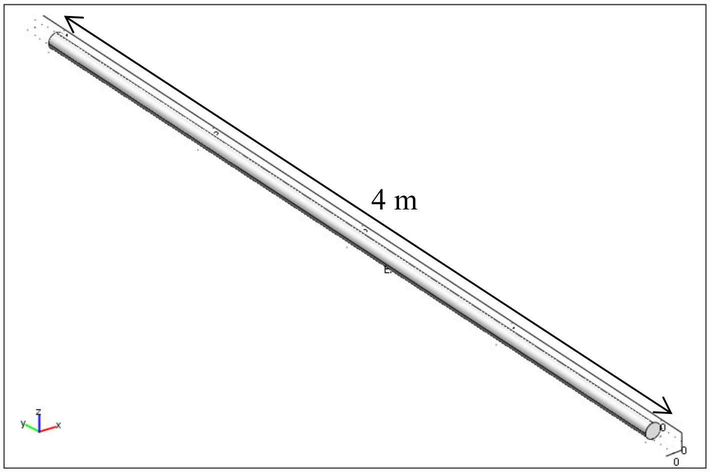


Figure 2 – System geometry.

3.2 Simplification of the geometry

The model size was reduced in order to minimise the calculation time, without loosing accuracy by making use of 2D axial symmetry. Consequently, the modelled domain is simply a rectangle, whose length represents the 1 m pipe length and width corresponds to the 1.5 in (0.0381 m) radius, as presented in Figure 3.

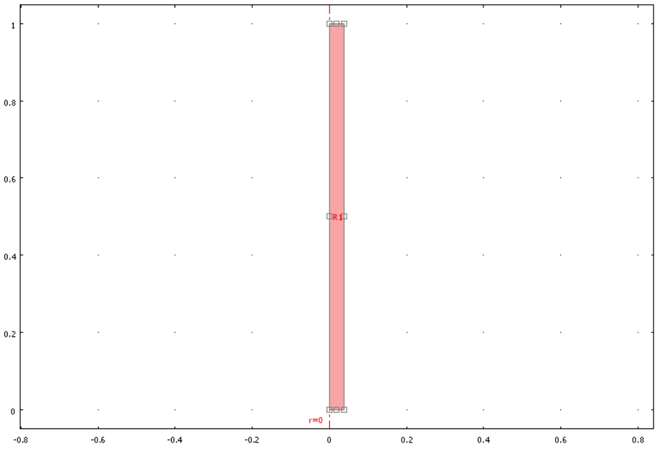


Figure 3 – Simplified geometry.

3.3 Meshing

In order to reach accurate results for the pressure drop, the mesh selected was a mapped mesh consisting of quadrilateral elements. This kind of mesh is structured in its pattern, and is recommended for geometries such that domains are fairly regular in shape and do not contain holes, as is the case. As can be seen in Figure 4, the mesh is more refined near the wall to resolve the so-called viscous sublayer, so that more precise modelling results can be obtained.

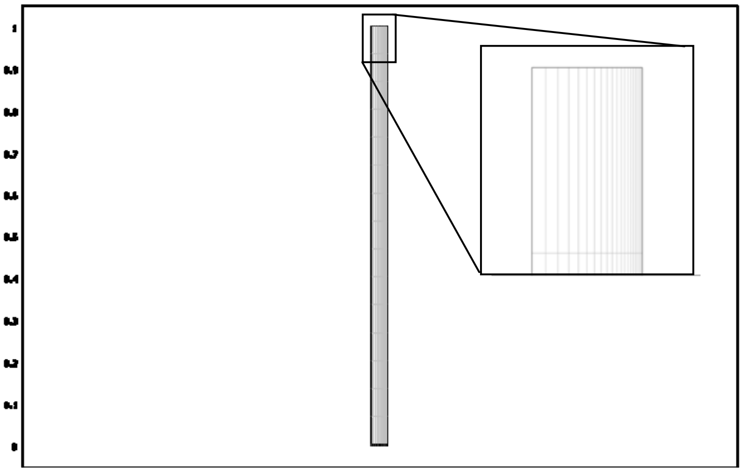


Figure 4 – Mesh mode.

3.4 Physics and boundaries

Subdomain settings	Physical characterization of the system regarding density and viscosity values: ▪ Density: collected experimentally by picnometry; ▪ Viscosity: collected experimentally by the use of a new viscometer specially designed to study multiphase systems. The viscosity values were introduced on the model as a velocity function, since the pulp fibre suspensions are clearly non-Newtonian fluids. The introduced viscosity models were constructed and fully discussed in a previous work [9].

Inlet boundary	The inlet fluid velocity was taken as a boundary condition, considering a uniform cross section velocity profile. Additionally, specific values for the two turbulent quantities, k and ε were required. Alternatively, a turbulent length scale, L_T, and a turbulent intensity scale, I_T, could be specified, which are related with the turbulent parameters as follows: $k = \frac{3}{2}\left(\lvert U \rvert\, I_T\right)^2$ (7) $\varepsilon = C_{\mu}^{3/4}\, \frac{k^{3/2}}{L_T}$ (8) These turbulence properties are more intuitive to understand and can more easily be related to the physical characteristics of the problem. The values of I_T and L_T are not exactly known, but they can be estimated following some guidelines from the literature [7]. $I_T = I\ \mathrm{Re}_{D_h}^{-1/8}$ (9) $L_T = l\ D_h$ (10) With no further information, generally, the I and l parameters values are frequently assumed to be 0.16 and 0.07, respectively. It is well referenced in previous studies that, the existence of particles, such as fibres, in a fluid flow, induces a turbulence damping [1, 10], which is reflected on the turbulence parameters decrease, thus the I and l values should be smaller than usually assumed for homogeneous fluids. However, the turbulence damping range and, hence, the I and l decrease are not exactly known; for pulp fibre suspensions it is expectable that the damping effect will depend on fibre type and on the consistency value. Taking into account the aforementioned discussion, and in order to simulate the turbulence damping, for both the I and l values of the modelling equations 9 and 10, smaller values than usually used for homogeneous fluids were introduced in the model. Since the turbulent length scale is mentioned to be mainly dependent on the system geometry, the l value was assumed to be constant for all the fibre types and all the consistencies. The I parameter was adjusted according to the pulp fibre type and concentration.
Outlet boundary	The condition “Normal Stress, Normal Flow” was chosen to describe the outlet condition of the domain, since this condition determines that there must be no tangential velocities on the boundary.
Wall	The wall boundary selected for the model must consider that turbulence close to a solid wall is very different from isotropic free-stream turbulence. To overcome this fact, an approach considering an empirical relation between the value of velocity and wall friction was introduced in the model. This relation known as “wall function” is accurate for high Reynolds numbers and in situations where pressure variations along the wall are not very large [7], which can be assumed in the case reported here. The wall boundary was modelled with a logarithm wall function; this wall function translated into finite elements assumes that the computation domain begins at a distance δ_W from the real wall. The δ_W value considered in this research was 0.0025m, 6% of the pipe radius, in agreement with the the recommendations of COMSOL for this kind of situation. The logarithm wall function also assumes that the velocity is parallel to the wall.

Symmetry boundary	The “Axial Symmetry” condition should be used on all boundaries with coordinate r=0.

3.5 Solver

Different solvers were tested but the best results were achieved through the use of a “Parametric Segregated” solver, which actually is indicated for parameterized sets of stationary multiphysics PDE problems (linear or nonlinear). In the present study, the mentioned solver was used to find the solution for an increasing sequence of velocities.

4. Results and Discussion

Firstly, the numerical implementation was validated with water, considering the water physical characteristics. Then, the pulp’s physical characteristics were introduced in the model. It was considered that the suspensions start to flow in fully developed turbulence at velocities above the maximum of the drag reduction effect - V_{red} (see Figure 1).

As an example of an output result, Figure 5 shows the simulated pressure drop along 1 m of pipe for the specific case of the recycled pulp suspension with 2.7% (w/w) consistency, at a velocity of 4.8 m/s.

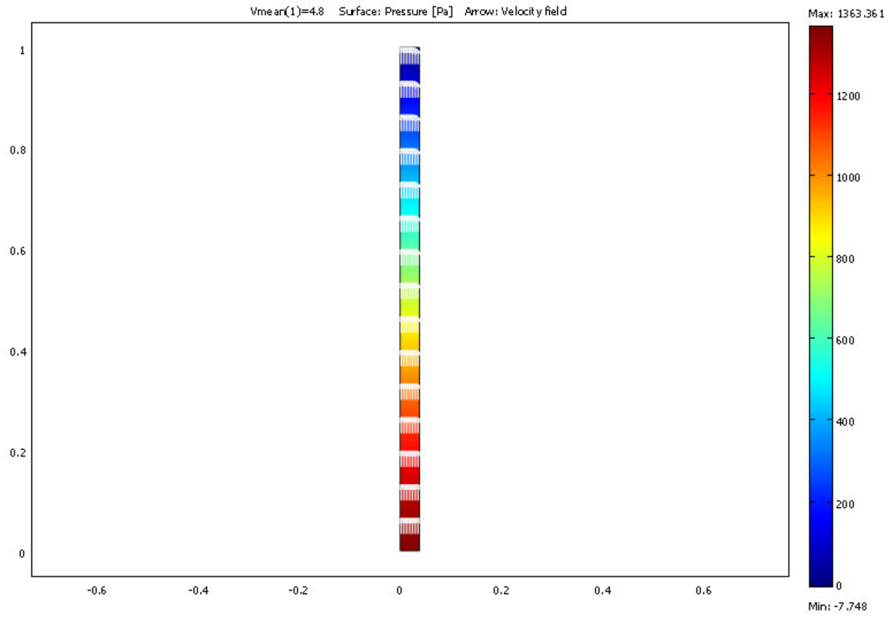
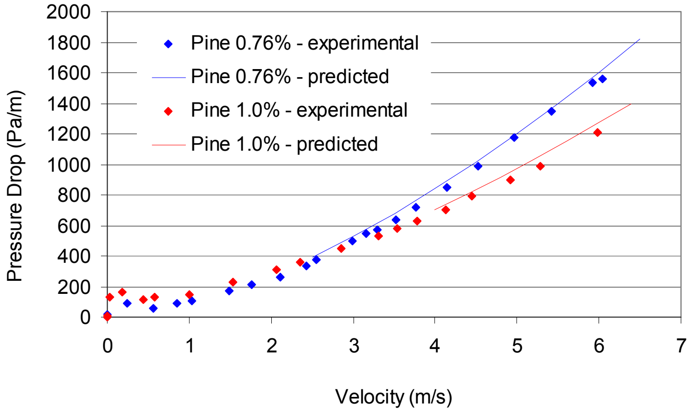


Figure 5 – Simulated pressure drop for the flow of the recycled pulp suspension with 2.7% (w/w) consistency, at a velocity of 4.8 m/s.

It can be seen the pressure drop profile along 1 m of pipe represented by the colour variation and the velocity profile along the pipe length represented by the white arrows. As expected, the simulation results confirm that the pressure decreases along the pipe and, since the system is highly turbulent, that the radial velocity profile remains stable along the pipe.

The model's pressure drop results for each consistency and pulp type were compared with the experimental pressure drop results, and the model's turbulence parameters were adjusted until a good fit with the experimental results was obtained. An example is shown in Figure 6.



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

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

Figure 6 – Experimental versus predicted fit for the pressure drop of pine pulp suspensions at 0.76% and 1.0% of consistency.

Figure 6 shows that the turbulence parameters used to simulate the flow of the pine suspension for the specified conditions led to a good fit between the experimental and predicted values. From the many simulations performed for the different pulps and consistencies, the turbulence parameters values reported in Table 1 were found to be adequate for use at the several flow conditions.

Table 2 - Turbulence parameters values.

<table>
<tr><th>Pulp type</th><th>Turbulence Parameters</th><th colspan="6">very low consistencies</th><th colspan="12">low consistencies</th></tr>
<tr><td rowspan="3">Recycled</td><td>Consistency (%)</td><td colspan="2">0.72</td><td colspan="2">0.60</td><td colspan="2">0.61</td><td colspan="3">1.40</td><td colspan="3">1.80</td><td colspan="3">2.30</td><td colspan="3">2.70</td></tr>
<tr><td>I</td><td colspan="2">0.01</td><td colspan="2">0.01</td><td colspan="2">0.01</td><td colspan="3">0.009</td><td colspan="3">0.008</td><td colspan="3">0.007</td><td colspan="3">0.005</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="3">0.005</td><td colspan="3">0.005</td><td colspan="3">0.005</td><td colspan="3">0.005</td></tr>
<tr><td rowspan="3">Eucalypt</td><td>Consistency (%)</td><td colspan="3">0.77</td><td colspan="3">0.91</td><td colspan="6">1.4</td><td colspan="6">1.5</td></tr>
<tr><td>I</td><td colspan="3">0.09</td><td colspan="3">0.09</td><td colspan="6">0.007</td><td colspan="6">0.003</td></tr>
<tr><td>l</td><td colspan="3">0.005</td><td colspan="3">0.005</td><td colspan="6">0.005</td><td colspan="6">0.005</td></tr>
<tr><td rowspan="3">Eucalypt + pine</td><td>Consistency (%)</td><td colspan="3">0.71</td><td colspan="3">0.77</td><td colspan="4">0.9</td><td colspan="4">1.2</td><td colspan="4">1.3</td></tr>
<tr><td>I</td><td colspan="3">0.07</td><td colspan="3">0.05</td><td colspan="4">0.01</td><td colspan="4">0.005</td><td colspan="4">0.003</td></tr>
<tr><td>l</td><td colspan="3">0.005</td><td colspan="3">0.005</td><td colspan="4">0.005</td><td colspan="4">0.005</td><td colspan="4">0.005</td></tr>
<tr><td rowspan="3">Pine</td><td>Consistency (%)</td><td colspan="3">0.66</td><td colspan="3">0.76</td><td colspan="6">0.8</td><td colspan="6">1</td></tr>
<tr><td>I</td><td colspan="3">0.01</td><td colspan="3">0.01</td><td colspan="6">0.0005</td><td colspan="6">0.0003</td></tr>
<tr><td>l</td><td colspan="3">0.005</td><td colspan="3">0.005</td><td colspan="6">0.005</td><td colspan="6">0.005</td></tr>
</table>

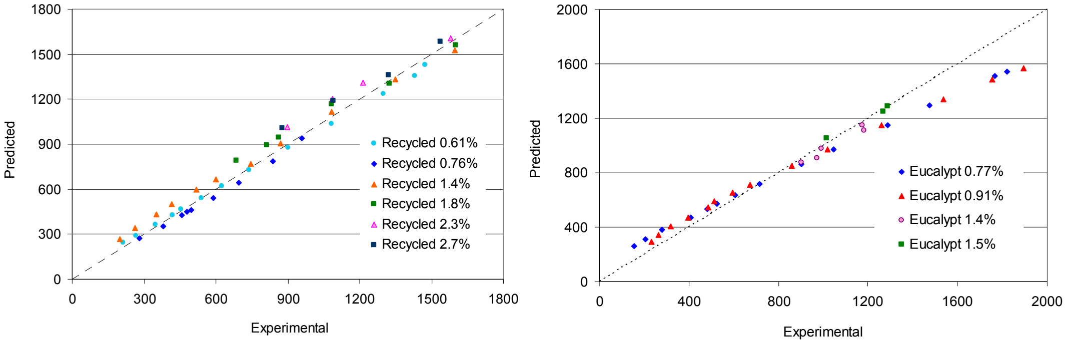
From Table 1 it can be easily concluded that for very low consistencies the I value is minimally influenced by the consistency increase, this means that a slight variation in consistency for these consistencies range does not modify the turbulent flow mechanisms.

Contrarily, for relatively high values of consistency it is observed that as the consistency increases, the I values decreases for all the pulps. This trend was expected, since the presence of solids has an increasing damping effect on the longitudinal turbulence intensity, in agreement with previous studies [10]. Considering the unique characteristics of pulp fibre suspensions, whose components are able to develop new "suspension structures", such as floccettes and flocs, it can be easily understood the larger decrease of the I value, since these "new" structures, which are not only bigger, but also of a different nature, modify the suspension turbulence characteristics.

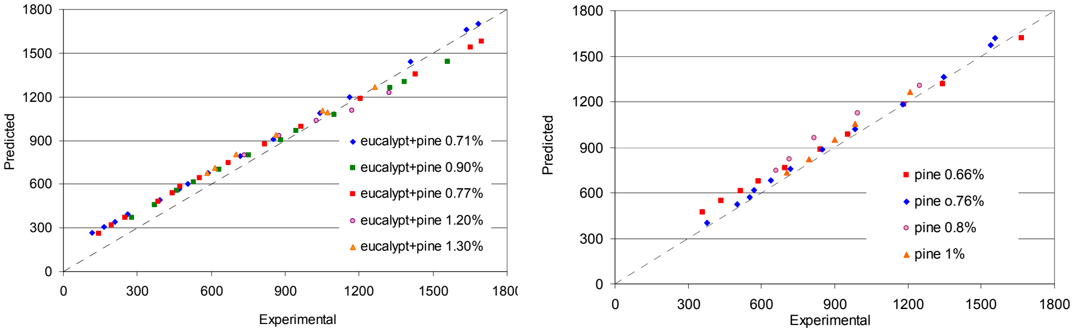
The highest values of turbulence damping were observed for the pine fibre suspension, followed by the eucalypt+pine and the eucalypt pulp suspensions. This fact is certainly related with both the fibres length and the fibres morphological characteristics. Pine fibres are the longest and stiffest ones.

Regarding the recycled pulp suspension the effect of consistency was not so important. In fact, this different behaviour has already been recognised in other situations, such as the rheological and flow behaviours [9, 11,12]: this is certainly related to the intrinsic pulp suspension characteristics, such as the presence of other components including adhesives, ink and waste particles, which modify not only its fundamental nature, but also its visual appearance. Actually, this was the pastiest suspension and for this reason it looked more homogenous.

In Figure 7 a comparison between the experimental data and the modelling results for the flow conditions tested (different pulps and consistencies) is presented:



a) recycled b) eucalypt



c) eucalypt+pine d) pine

Figure 7 - Comparison between the experimental pressure drop data and the modelling results for the flow conditions tested.

The predicted values for the pressure drop in pipes are very similar to the experimental ones. Regarding the lowest values of pressure drop for the fresh pulp fibre suspensions, a more careful observation shows that the simulation results slightly over-predict. These values correspond to the lowest flow velocities, so this difference can be due to the fact that for these velocities the turbulent flow regime may not be completely established.

Considering the eucalypt fibre suspension (Figure 9 b)) the CFD model is not completely able to predict pressure drop for the highest velocities: the calculated values are smaller than the experimental ones. These values correspond to the lowest consistencies at the highest velocities, and the observed trend may be due to the experimental rheological values used. In fact, due to limitations of the rheometer, very high shear velocities were impossible to reach and these values had to be extrapolated from the rheogram.

5. Conclusions

The pressure drop profiles obtained using COMSOL Multiphysics Software agree very well with the experimental results obtained in a pilot rig for the turbulent flow regime. Moreover, the use of the $k-\varepsilon$ Turbulence Model for the simulation of pulp fibre suspensions flow, associated with the rheological data acquired in a viscometer especially designed to study multiphase systems, revealed to be an interesting and accurate strategy to attain good prediction of pressure drop values for fibre suspension flow.

The adjustment of the turbulence parameters confirms previous studies, where it was concluded that the existence of particles, such as fibres, in a fluid flow, induces a turbulence damping. The turbulence intensity scale, I_T (as a function of I), decreases with pulp consistency increase.

6 Acknowledgments

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