The correct design of piping transport systems for pulp fiber suspensions in pulp and paper mills is important because of the large energy consumption involved. Papermakers need consistent and complete correlations to predict the friction loss in pipes in order to optimize the pulp conveying.

The flow mechanisms of pulp fiber suspension in pipes have been distinguished in three different systems. At low velocities the suspension flows as a plug of fibers 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 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. At intermediate velocities, there is a transition system where a central and intact plug is surrounded by a turbulent fiber-water annulus. This is termed transition flow and it starts at the onset of the drag reduction effect. Transition flow is illustrated in Fig. 1 where pressure drop \( \frac{\Delta H}{L} \) is plotted against velocity [1–6].

Despite all the research in this area, an examination of the published friction loss data reveals wide discrepancies, under apparently similar conditions [7]. The majority of the published design correlations refer to the flow system before the maximum in the head loss curve \( (V_{\text{max}}) \), and there is a general agreement on the application of Eq. 1 to this flow system [8–10]:

\[
\frac{\Delta H}{L} = K V^\alpha \ \text{Cons}^\beta D_p^\gamma
\]  

(1)

where \( \frac{\Delta H}{L} \) is the friction head loss \( \left( \frac{\text{mH}; \text{O} / 100 \text{m pipe}}{\text{V}} \right) \); \( V \) is the bulk velocity \( \left( \frac{\text{m}}{\text{s}} \right) \); \( \text{Cons} \) is the pulp consistency (%); \( D_p \) is the internal pipe diameter \( (\text{mm}) \); \( K \) is a numerical coefficient, constant for a given pulp; and \( \alpha, \beta, \gamma \) are exponents, assuming also constants values for a given pulp.

For velocities above the maximum in the head loss curve, the published literature is incomplete and poor. Our study's purpose was to improve the knowledge by defining design correlations for the flow of different kinds of industrial pulp fiber suspensions, at the flow system before the maximum in the head loss curve and also after the onset of turbulence in the water annulus \( (V_{\text{WT}}) \).

**MATERIALS AND METHODS**

We designed, assembled, tested, and calibrated a pilot rig for this study. Figure 2 illustrates the experimental setup.

The stainless steel (SS) or polyethylene (PE) test sections were 7.5 m in length and had a changeable diameter of 0.0381 m, 0.0762 m, or 0.1068 m. The flow rate was regulated by two valves and measured by an electromagnetic flowmeter. The pressure drop was measured by a differential pressure transducer, whose pressure taps were 4 m apart. Enough pipe length was allowed before...
and after the pressure taps, so that both entrance and end effects could be neglected. We studied four different industrial pulp suspensions (recycled pulp, eucalypt bleached kraft pulp, pine unbleached kraft pulp and eucalypt [90%] + pine [10%] pulp bleached pulp suspension) in the pilot rig.

We established an experimental design to evaluate the relative influence of pulp consistency, pipe material, pipe diameter, and pulp velocity on the flow of each pulp fiber suspension. Thereafter, for each pulp and flow system, we proposed a mathematical model considering the four parameters to estimate the pressure drop of pulp fiber suspensions in pipes. The flow results were analyzed using the Design Expert® software. We also analyzed the influence of fiber length on the model parameters. For that, the length weighted mean fiber length of each pulp suspension was determined in the HiRes Fiber Quality Analyzer (OpTest Equipment Inc., Hawkesbury, Ontario, Canada) apparatus [11]. These results are presented in Table I.

<table>
<thead>
<tr>
<th>Pulp suspension</th>
<th>Recycled</th>
<th>Eucalypt</th>
<th>Pine + eucalypt</th>
<th>Pine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiber length (mm)</td>
<td>1.14±0.04</td>
<td>0.71±0.03</td>
<td>0.61±0.06</td>
<td>2.56±0.14</td>
</tr>
</tbody>
</table>

I. Length weighted mean fiber length of pulp fiber suspensions.

RESULTS AND DISCUSSION

Flow behavior of the pulp fiber suspensions

Figure 3 displays the experimental behavior of each industrial pulp fiber suspension tested in the 0.0762-m SS pipe. This trend was also found with the other pipes. It may be concluded that not only does the range of pressure drop differ from pulp to pulp, but also the beginning and the end of the transition are different for each pulp suspension. The fact that the recycled pulp suspension presented the lowest values for the pressure drop seems to be associated with an aging effect, which induces a decrease of the pressure drop in pipes. To confirm the aging, an industrial pine pulp suspension underwent one week of aging (Fig. 4). After this time, the suspension exhibited lower pressure drop values for the same velocities than the original suspension, thus confirming that aging can lead to a degradation of the suspension, probably similar to the refining effect, and induce lower pressure drops.

For the other pulps, as fiber length increased (Table I), the velocity at maximum in the head loss curve ($V_{max}$) increased too (Fig. 3). In fact, the increase of the fiber length allowed the flow at low velocities to stabilize. Fibers align in streamlines, and as fiber length increases this alignment remains stable until higher velocities are reached.

Modelling the flow behavior

For each pulp fiber suspension, the modelling of the flow results was performed in two different regions of the pressure drop curve: before the maximum in the head loss curve ($V_{max}$) and after the onset of turbulence in the water annulus ($V_{WT}$).
In general, the $V_{\text{max}}$ and $V_{\text{WT}}$ values increase with consistency. For each fiber type it was possible to correlate these velocities with suspension consistency. Table II summarizes the models that were developed. The long fiber suspension shows a higher dependence of the transition velocities on consistency. With the correlations presented, it is possible to clearly establish the initial or final velocity boundary conditions of the flow models.

**Flow models for velocities below $V_{\text{max}}$**

An example of a design made for pulps flowing at velocities below the maximum in the pressure drop curve is presented in Table III, considering the eucalypt pulp fiber suspension. For this flow system and for each pulp suspension we applied a logarithmic transformation for both factors and response, in order to achieve a mathematical model consistent with Eq. 1.

The equation (Eq. 2) in terms of the coded factors, which supplies information about the relative factor importance of the distinct parameters resulting from the statistical analysis of $\ln \left(\frac{AH}{L}\right)$ for the fiber suspension is as follows:

$$\ln \left(\frac{AH}{L}\right) = 1.46 + 1.68 A - 0.17 B - 0.02 C + 0.42 D \quad (2)$$

Considering the coded factors, consistency (A) is the most significant effect. Its variation has four times more impact in the response than velocity (D), 10 times more than pipe diameter (B), and 84 times more than pipe material (C). From these values it can be concluded that the pipe material effect has no significance for the pressure drop. Therefore, we performed a new iteration and obtained an improved model equation without considering the effect of pipe material for this suspension (Eq. 3):

$$\ln \left(\frac{AH}{L}\right) = 1.46 + 1.68 A - 0.16 B + 0.41 D \quad (3)$$

It is also clear that consistency (A) and velocity (D) have a positive effect on the response and pipe diameter (B) has a negative effect. A similar analysis was also done for the other pulp suspensions, and the corresponding results are presented in Table IV. For the recycled pulp the plug flow system was too short and, therefore, it was not possible to acquire representative data points to perform the analysis.

The results presented confirm the observations already made for the eucalypt pulp suspension (Eq. 2). Moreover, it may be concluded that the impact of each factor has the same magnitude regardless of the pulps considered, and that consistency is always the most important factor.

As mentioned, we also constructed a model in terms of the actual (real scale) factors and presented the results in Table V. Due to the generally negligible effect of pipe material, previously detected, we only considered the results corresponding to the SS pipes for the analysis. $R^2_{\text{adj}}$ is the adjusted correlation coefficient for the model, and this coefficient takes into account the number of terms in the model. We used this correlation coefficient to evaluate the model adequacy because

### Table II

<table>
<thead>
<tr>
<th>Design parameter</th>
<th>$\ln\left(\frac{AH}{L}\right)\left(mH,O/\text{100 m pipe}\right)$</th>
</tr>
</thead>
</table>

### Table III

<table>
<thead>
<tr>
<th>Design factors</th>
<th>Design levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\ln(\text{Cons})$ (%) - A</td>
<td>ln(0.84) ln(1.45) ln(1.80) ln(2.20) ln(2.50) ln(2.85) ln(3.20) ln(3.50)</td>
</tr>
<tr>
<td>$\ln(D_P)$ (mm) - B</td>
<td>ln(38.1) ln(76.2) ln(106.8)</td>
</tr>
<tr>
<td>$P_{\text{Material}}$ - C</td>
<td>SS PE</td>
</tr>
<tr>
<td>$\ln(V)$ ($m/s$) - D</td>
<td>ln(0.1) ln(0.25) ln(0.5) ln(0.75)</td>
</tr>
</tbody>
</table>

### Table IV

<table>
<thead>
<tr>
<th>Factors</th>
<th>Pulp suspension</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>eucalypt</td>
</tr>
<tr>
<td><strong>Constant</strong></td>
<td>1.46</td>
</tr>
<tr>
<td>A</td>
<td>1.68</td>
</tr>
<tr>
<td>B</td>
<td>-0.17</td>
</tr>
<tr>
<td>C</td>
<td>-0.02</td>
</tr>
<tr>
<td>D</td>
<td>0.42</td>
</tr>
</tbody>
</table>

### Table V

<table>
<thead>
<tr>
<th>Factors</th>
<th>Pulp suspension</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>eucalypt</td>
</tr>
<tr>
<td><strong>Constant</strong></td>
<td>1.99</td>
</tr>
<tr>
<td>$\ln(\text{Cons})$</td>
<td>2.36</td>
</tr>
<tr>
<td>$\ln(D_P)$</td>
<td>-0.33</td>
</tr>
<tr>
<td>$\ln(V)$</td>
<td>0.36</td>
</tr>
<tr>
<td>$R^2_{\text{adj}}$</td>
<td>0.961</td>
</tr>
</tbody>
</table>
the regular $R^2$ can be artificially inflated by simply continuing to add terms to the model, while $R^2_{adj}$ basically plateaus when insignificant terms are added to the model. Based on the values in Table V and Eq. 1, we can formulate the following model equations for each pulp (Eqs. 4–6):

Eucalypt pulp suspension:

$$\frac{\Delta H}{L} = 7.33 \text{ Cons}^{3.30} \text{ D_e}^{-0.35} \text{ V}^{3.86}$$

Cons e $[0.84\%, 3.50\%]$; $D_e$ e $[38.1 \mu m, 106.8 \mu m]$; $V$ e $[0.1 \text{ m/s}, 0.19 \text{ C}^{1.45} \text{ m/s}]$

Pine + eucalypt pulp suspension (10:90%, w/w):

$$\frac{\Delta H}{L} = 6.10 \text{ Cons}^{3.82} \text{ D_e}^{-0.33} \text{ V}^{0.42}$$

Cons e $[0.90\%, 3.20\%]$; $D_e$ e $[38.1 \mu m, 106.8 \mu m]$; $V$ e $[0.1 \text{ m/s}, 0.21 \text{ C}^{1.17} \text{ m/s}]$

Pine pulp suspension:

$$\frac{\Delta H}{L} = 6.10 \text{ Cons}^{3.82} \text{ D_e}^{-0.33} \text{ V}^{0.42}$$

Cons e $[0.80\%, 3.60\%]$; $D_e$ e $[38.1 \mu m, 106.8 \mu m]$; $V$ e $[0.1 \text{ m/s}, 0.15 \text{ C}^{1.10} \text{ m/s}]$

In addition to this analysis, we compared the design coefficients of all the pulps in terms of fiber length, as illustrated in Fig. 5. It can be concluded that the parameter $K$ is strongly influenced by the fiber length, while the influence is not so evident or conclusive for the other parameters. Table VI presents a comparison of the correlations we obtained for the plug flow system with those of TIP 0410-14 [6], based on Eq. 1. The correlations are not exact for the same pulps we tested so we considered the most similar pulp, in terms of fiber length.

Table VI shows that the values of $\alpha$, $\beta$ and $\gamma$ we obtained are in good agreement with those reported by TAPPI Standard TIP 0410-14. As for $K$, although there is a striking difference, this parameter is strongly influenced by the fiber characteris-

<table>
<thead>
<tr>
<th>Pulp type</th>
<th>Origin of data</th>
<th>$K$</th>
<th>$\alpha$</th>
<th>$\beta$</th>
<th>$\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eucalypt + pine bleached pulp suspension</td>
<td>Present study</td>
<td>6.10</td>
<td>0.47</td>
<td>2.82</td>
<td>-0.40</td>
</tr>
<tr>
<td></td>
<td>TIP 0410-14</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
</tr>
<tr>
<td>Eucalypt bleached pulp suspension</td>
<td>Present study</td>
<td>7.33</td>
<td>0.36</td>
<td>2.36</td>
<td>-0.33</td>
</tr>
<tr>
<td></td>
<td>TIP 0410-14 Kraft birch dried and res slurried</td>
<td>2182</td>
<td>0.27</td>
<td>1.78</td>
<td>-1.08</td>
</tr>
<tr>
<td>Pine unbleached pulp suspension</td>
<td>Present study</td>
<td>44.1</td>
<td>0.26</td>
<td>2.31</td>
<td>-0.80</td>
</tr>
<tr>
<td></td>
<td>TIP 0410-14 Long-fibered Kraft never dried CSF=650</td>
<td>11502</td>
<td>0.31</td>
<td>1.81</td>
<td>-1.34</td>
</tr>
</tbody>
</table>

n.a. – not available.

$K$ values determined at 42°C.

VI. Parameters of Eq. 1: present study vs. TAPPI values (TIP 0410-14).
of consistency and velocity. Table VII presents the results of the experimental design approach. The impact of each factor in pressure drop is similar for all pulps and the pipe material (C) has almost no effect in the pressure drop at velocities above the drag reduction effect. Consistency (A) has a strong influence on all the pulps, but pipe diameter (B) and pulp velocity (D) are the most important factors for the recycled and the mixture of eucalypt and pine pulp suspensions. In fact, for these two pulp suspensions the pressure drop was lower and its variation was not so pronounced. Consequently, a major similarity to the water behavior was observed even at high consistencies. Pipe diameter has a strong impact on the pressure drop for all the pulps.

The velocity is also a significant factor, having the strongest effect on the recycled and mixed pulp suspension. Furthermore, for this flow system regime the preponderance of the consistency effect on the response is less evident, probably because the fiber flocs must be completely disrupted in this region.

A correlation in terms of real factors can be written for each type of pulp fiber suspension, considering the results relative to the SS pipes. The resultant equations (Eqs. 7–10) are:

Recycled pulp suspension:

\[
\frac{\Delta H}{L} = \frac{30.72 + 21.18 \text{Cons} - 1077.45 D_p + 16.85 V}{-196.98 \text{Cons} \cdot D_p - 3.12 \text{Cons} \cdot V - 837.72 D_p \cdot V} + 1.95 \text{Cons}^2 + 6890.93 D_p^2 + 3.19 V^2
\]

\( \text{Cons} \in [0.70\%a, 4.30\%a]; \ D_p \in [0.038\text{in}, 0.1068\text{in}]; \ V \in [1.5 \text{m/s}, 6.0 \text{m/s}] \)

\( R^2_{adj} = 0.980 \)

<table>
<thead>
<tr>
<th>Factors</th>
<th>Pulspension</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>recycled</td>
</tr>
<tr>
<td>Constant</td>
<td>68.73</td>
</tr>
<tr>
<td>A</td>
<td>9.09</td>
</tr>
<tr>
<td>B</td>
<td>-22.49</td>
</tr>
<tr>
<td>C</td>
<td>3.45</td>
</tr>
<tr>
<td>D</td>
<td>68.00</td>
</tr>
<tr>
<td>AB</td>
<td>-12.18</td>
</tr>
<tr>
<td>AC</td>
<td>-1.82</td>
</tr>
<tr>
<td>AD</td>
<td>-13.49</td>
</tr>
<tr>
<td>BC</td>
<td>6.92</td>
</tr>
<tr>
<td>BD</td>
<td>-6.91</td>
</tr>
<tr>
<td>CD</td>
<td>8.83</td>
</tr>
<tr>
<td>A2</td>
<td>6.33</td>
</tr>
<tr>
<td>B2</td>
<td>8.13</td>
</tr>
<tr>
<td>D2</td>
<td>18.36</td>
</tr>
</tbody>
</table>

VII. Coefficients of the coded factors for each pulp suspension for velocities above \( V_{WT} \)
Eucalypt pulp suspension:

\[
\frac{\Delta H}{L} = 115.50 + 48.10 \, Cons - 3007.98 \, Dp + 26.61 \, V
\]

\[
-1817.31 \, Cons \, Dp - 0.23 \, Cons \, V - 162.26 \, Dp \, V
\]

+ 34.15 \, Cons^{2} + 27091.14 \, Dp^{2} + 2.23 \, V^{2}

\[Cons \in [0.84\%, \, 3.50\%] ; \, Dp \in [0.038 \, \text{in}, \, 0.1068 \, \text{in}] ; \, V \in [0.60 \, C^{0.3} \, m/s, \, 6.0 \, m/s] \]

\[R_{adj}^{2} = 0.972\]

Pine + eucalypt pulp suspension (10:90%, w/w):

\[
\frac{\Delta H}{L} = 109.38 + 11.48 \, Cons - 3529.41 \, Dp + 46.90 \, V
\]

\[-203.13 \, Cons \, Dp + 0.02 \, Cons \, V - 384.42 \, Dp \, V
\]

+ 9.17 \, Cons^{2} + 23785.36 \, Dp^{2} + 1.22 \, V^{2}

\[Cons \in [0.90\%, \, 3.20\%] ; \, P_{pulpr} \in [0.038 \, \text{in}, \, 0.1068 \, \text{in}] ; \, V \in [0.47 \, C^{0.3} \, m/s, \, 6.0 \, m/s] \]

\[R_{adj}^{2} = 0.957\]

Pine pulp suspension:

\[
\frac{\Delta H}{L} = 23.69 - 44.60 \, Cons + 7.17 \, V - 3.21 \, Cons \times V + 26.41 \, Cons^{2} + 2.55 \, V^{2}
\]

\[Cons \in [0.80\%, \, 3.60\%] ; \, V \in [0.38 \, C^{0.3} \, m/s, \, 6.0 \, m/s] \]

Finally, we must stress that the model’s coefficients of correlation are very good, regardless of the flow system and the range of velocities considered.

**CONCLUSIONS**

The experimental results confirm that pulp flow is influenced by the type of pulp fiber because pressure drop and velocity at the beginning of turbulence differ from one pulp suspension to another. Nevertheless, for the plug flow system we can conclude that the impact of each factor in the pressure drop is similar for all the pulps and that consistency is the most important factor in all the cases, followed by pulp velocity and pipe diameter.

As for the models constructed for velocities above the drag reduction effect, we found no general rule regarding the most important factor although the pressure drop behavior is strongly influenced by consistency, pipe diameter, and velocity. The preponderance of the consistency impact on pressure drop for this system is not so evident. The influence of the pipe material on the models we developed was negligible for both systems studied. TJ

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**INSIGHTS FROM THE AUTHORS**

An interest in particle technology and multiphase flows led us to investigate the relationship between particle characteristics and flow behavior of suspensions. Fibers can be considered as particles, so it was just a question of extending the investigation into an application important to our industrial partners.

The statistical design involved in the work, as well as data we collected on specific industrial pulps, allowed us to understand the most significant factors for the pulp flow.

Our biggest challenge was the experimental part and its preparation, because each trial involved the collection and management of 1000 L of pulp fiber suspensions. It was also difficult to change the experimental trial pipes without any mechanical help.

An unexpected finding was the atypical behavior of the recycled pulp suspension. We also found that consistency is not the most important factor for high velocities.

Our work will benefit mills by supplying information about the flow behavior of industrial pulp fiber suspensions and insight into designing transport systems. The next step is to provide information about a new way to determine pulp viscosity.

Ventura is a doctoral candidate, Ferreira is an auxiliary professor, and Garcia and Rasteiro are associate professors in the Chemical Engineering Department, University of Coimbra, Coimbra, Portugal; Email Rasteiro at mgr@eq.uc.pt.
PULPING

NOMENCLATURE

A, B, C, D, AB, AC, AD, BC, CD, A2, B2, D2 — coded model factors;

Cons — pulp consistency;

K — numerical coefficients, constant for a given pulp;

Dp — internal pipe diameter;

P_{\text{Material}} — pipe material;

R^2 — correlation coefficient;

R^2_{\text{adj}} — adjusted correlation coefficient;

V — bulk velocity;

V_{\text{max}} — velocity at the maximum in the head loss curve;

V_{\text{WT}} — velocity at the onset of turbulence in the water annulus;

V_w — velocity at the onset of the drag reduction effect;

\alpha, \beta, \gamma — exponents, constants for a given pulp;

\frac{\Delta H}{L} — friction head \left(\frac{mH_2O}{100\text{m pipe}}\right).

LITERATURE CITED

8. TAPPI TIP 0410-14 “Generalized method for determining the pipe friction loss of flowing pulp suspensions,” TAPPI, Atlanta, Georgia, USA.

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