Flow dynamics of pulp fiber suspensions

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ABSTRACT: The transport between different equipment and unit operations plays an important role in pulp and paper mills because fiber suspensions differ from all other solid-liquid systems, due to the complex interactions between the different pulp and paper components. Poor understanding of the suspensions' flow dynamics means the industrial equipment design is usually conservative and frequently oversized, thus contributing to excessive energy consumption in the plants. Our study aim was to obtain additional knowledge about the dynamic behavior of industrial pulp suspensions in order to evaluate the relative importance of the factors that influence pressure drop. To obtain mathematical correlations to quantify pressure drop for the transport of pulp suspensions, we studied four different industrial pulp suspensions (recycled pulp, eucalypt bleached kraft pulp, pine unbleached kraft pulp, and eucalypt [90%] + pine [10%] bleached kraft pulp) in a pilot rig specially designed and built for the effect.

Application: Clear understanding of pulp flow dynamics will be useful for optimum design and operation of the conveying systems in pulp and paper plants.

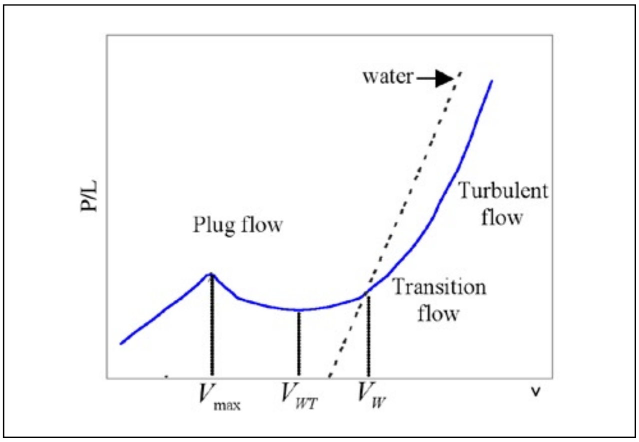
The correct design of piping transport systems for pulp fiber suspensions in pulp and paper mills is important because of the large energy consumption involved. Papermakers need consistent and complete correlations to predict the friction loss in pipes in order to optimize the pulp conveying.

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 $\left(\frac{\Delta P}{L}\right)$ 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_{max}), and there is a general agreement on the application of Eq. 1 to this flow system [8–10]:

$$\frac{\Delta H}{L} = K\, V^{\alpha}\, Cons^{\beta}\, D_P{}^{\gamma} \tag{1}$$

where $\frac{\Delta H}{L}$ is the friction head loss $\left(mH_2O/_{100m\ pipe}\right)$; V is the bulk velocity $\left(m/_{s}\right)$; $Cons$ is the pulp consistency (%); D_P is the internal pipe diameter (mm); K is a numerical coefficient, constant for a given pulp; and α, β, γ are exponents, assuming also constants values for a given pulp.



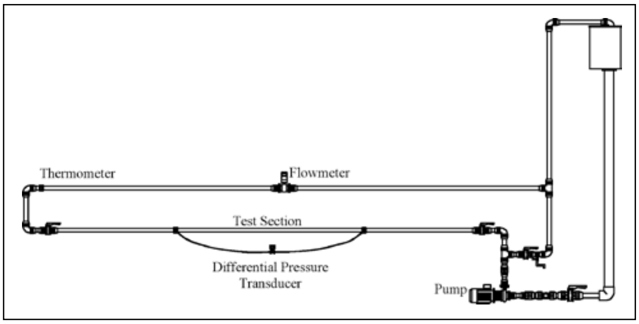
1. Typical friction loss curve [4].

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_{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



2. Pilot rig.

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**.

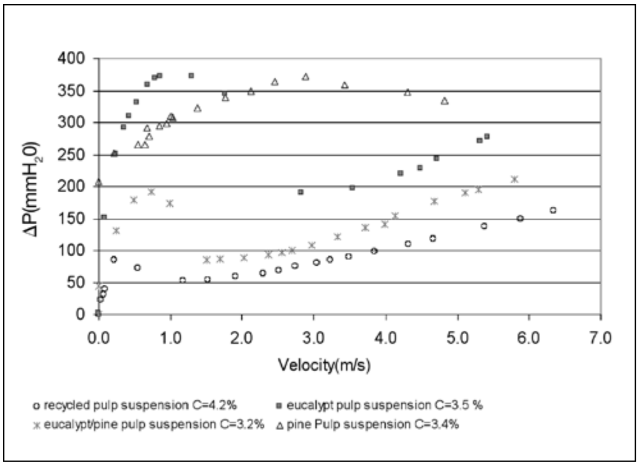
Pulp suspension	Recycled	Eucalypt	Pine + eucalypt	Pine
Fiber length (mm)	1.14±0.04	0.71±0.03	0.61±0.06	2.56±0.14

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

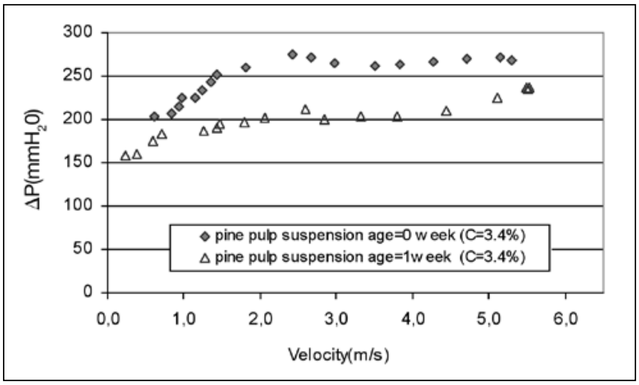
RESULTS AND DISCUSSION

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.



3. Pressure drop curve for the tested pulps at high consistencies (0.0762-m SS pipe).



4. Aging effect on a pine pulp fiber suspension (0.0762-m SS pipe).

Fiber suspension	V_{max}	V_{WT}
Recycled	---	$V \approx 1.5\ {}^{m}/_{s}$
Eucalypt	$V_{max} = 0.19\ C^{1.45}\ {}^{m}/_{s}$	$V = 0.60\ C^{1.21}\ {}^{m}/_{s}$
Pine + eucalypt	$V_{max} = 0.21\ C^{1.12}\ {}^{m}/_{s}$	$V = 0.47\ C^{1.21}\ {}^{m}/_{s}$
Pine	$V_{max} = 0.15\ C^{2.00}\ {}^{m}/_{s}$	$V = 0.38\ C^{1.86}\ {}^{m}/_{s}$

II. V_{max} and V_{WT} correlations.

For the other pulps, as fiber length increased (Table 1), 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 increase 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}).

Design parameter	$\ln\left(\frac{\Delta H}{L}\right)\left(\frac{mH_2O}{100m\ pipe}\right)$

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

III. Design structure for the eucalypt pulp suspension.

In general, the V_{max} and V_{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_{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 $\ln\left(\frac{\Delta H}{L}\right)$ for the fiber suspension is as follows:

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

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):

$$\ln\left(\frac{\Delta H}{L}\right) = 1.46 + 1.68\,A - 0.16\,B + 0.41\,D \qquad (3)$$

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.

Factors	Pulp suspension		
	eucalypt	pPine + eucalypt	pine
Constant	1.46	0.84	1.52
A	1.68	1.79	1.74
B	-0.17	-0.20	-0.41
C	-0.02	-0.22	0.01
D	0.42	0.47	0.42

IV. Coefficients of the coded factors for each pulp suspension for the plug flow system.

Factors	Pulp suspension		
	eucalypt	pine + eucalypt	pine
Constant	1.99	1.81	3.79
ln $(Cons)$	2.36	2.82	2.31
ln (D_P)	-0.33	-0.39	-0.80
ln (V)	0.36	0.47	0.26
R^2_{adj}	0.961	0.950	0.971

V. Coefficients of the actual factors for each pulp suspension for the plug flow system, referent to the SS pipes.

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_{adj} is the adjusted correlation coefficient for the model, and this coefficient takes in account the number of terms in the model. We used this correlation coefficient to evaluate the model adequacy because 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:

$$\frac{\Delta H}{L} = 7.33 \quad Cons^{2.36} \quad D_P^{-0.33} \quad V^{0.36} \qquad (4)$$

$$Cons \in [0.84\%, 3.50\%];\ D_P \in [38.1mm, 106.8mm];\ V \in [0.1\,{}^{m}\!/_{s}, 0.19\,C^{1.45}\,{}^{m}\!/_{s}]$$

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

$$\frac{\Delta H}{L} = 6.10 \quad Cons^{2.82} \quad D_P^{-0.39} \quad V^{0.47} \qquad (5)$$

$$Cons \in [0.90\%, 3.20\%];\ D_P \in [38.1mm, 106.8mm];\ V \in [0.1\,{}^{m}\!/_{s}, 0.21\,C^{1.12}\,{}^{m}\!/_{s}]$$

Pine pulp suspension:

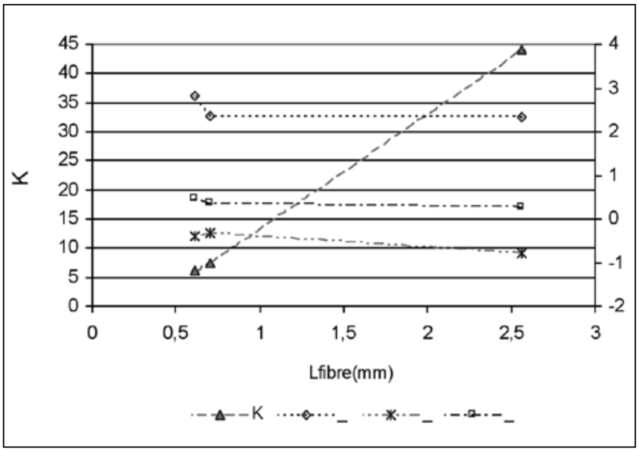
$$(6)$$

$$Cons \in [0.80\%, 3.60\%];\ D_P \in [38.1mm, 106.8mm];\ V \in [0.1\,{}^{m}\!/_{s}, 0.15\,C^{2.00}\,{}^{m}\!/_{s}]$$

$$V \in [0.1\,{}^{m}\!/_{s}, 0.15\,C^{2.00}\,{}^{m}\!/_{s}]$$

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 α, β and γ 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 characteristics and by the process conditions, namely bleaching and beating conditions. For example, this value can double from the unbleached to the bleached pulp suspension [6].



5. Parameters of Eq.1 vs. fiber length.

Figure 6 and **Fig. 7** illustrate two examples of the comparison between the experimental pressure drop, the values obtained by the model presented in this work and by the model presented in TAPPI Standard TIP 0410-14, for velocities below. In general, the present model appears to be a better fit with the experimental data.

Flow models for velocities above V_{WT}

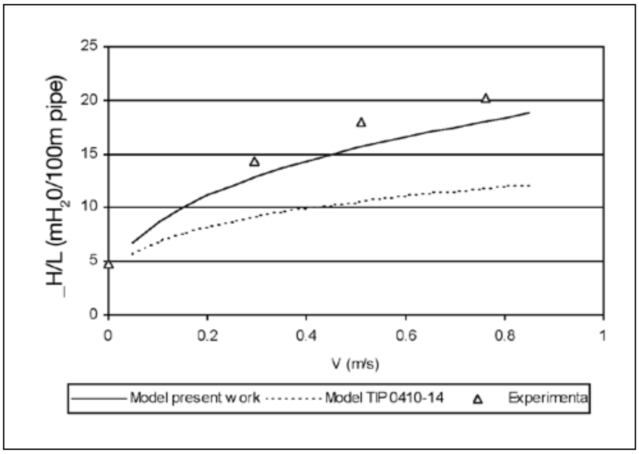
As mentioned before, we also attempted to model the flow for the velocities above the onset of turbulence in the water annulus (V_{WT}). A design analogous to the previous one was created for all the pulps, but no transformations were done because there was no pre-established general equation to follow. Furthermore, not only the single effects of each factor but also their double interactions, as well as the square of each factor, were introduced in the model. For the pine pulp suspension it was not possible to reach this at the highest consistency (for which all the pipes were tested), so we only studied the effect

Pulp type	Origin of data	K	α	β	γ
Eucalypt + pine bleached pulp suspension	Present study	6.10	0.47	2.82	-0.40
	TIP 0410-14	n.a.	n.a.	n.a.	n.a.
Eucalypt bleached pulp suspension	Present study	7.33	0.36	2.36	-0.33
	TIP 0410-14 Kraft birch dried and reslurried	2182	0.27	1.78	-1.08
Pine unbleached pulp suspension	Present study	44.1	0.26	2.31	-0.80
	TIP 0410-14 Long-fibered Kraft never dried CSF=650	11502	0.31	1.81	-1.34

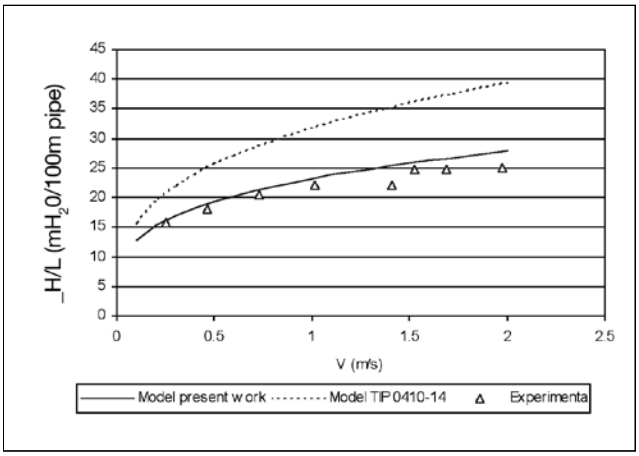
n.a. – not available.

K values determined at 42°C.

VI. Parameters of Eq. 1: present study vs. TAPPI values (TIP 0410-14).



6. Comparison of experimental and calculated pressure drop values for the eucalypt pulp suspension at 2.80% flowing in the 76.2-mm SS pipe.



7. Comparison of experimental and calculated pressure drop values for the pine pulp suspension at 3.4% flowing in the 76.2-mm SS pipe.

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:

$$\frac{\Delta H}{L} = \begin{array}{l} 30.72 + 21.18\,Cons - 1077.45\,D_P + 16.85\,V \\ -196.98\,Cons \bullet D_P - 3.12\,Cons \bullet V - 83.72\,D_P \bullet V \\ +1.95\,Cons^2 + 6890.93\,D_P{}^2 + 3.19\,V^2 \end{array} \qquad (7)$$

$$Cons \in [0.70\%, 4.30\%];\ \ D_P \in [0.0381m, 0.1068m];\ V \in [1.5\,{}^{m}\!/\!{}_{s}, 6.0\,{}^{m}\!/\!{}_{s}]$$

$$R^2_{adj} = 0.980$$

Factors	Pulp suspension			
	recycled	eucalypt	pine + eucalypt	pine
Constant	68.73	130.97	101.38	89.69
A	9.09	89.31	35.44	83.39
B	-22.49	-93.04	-56.97	-
C	3.45	1.97	2.20	-
D	68.00	57.84	77.23	43.31
AB	-12.18	-83.02	-8.02	-
AC	-1.82	4.69	-4.16	-
AD	-13.49	-0.45	0.05	-10.11
BC	6.92	35.98	9.70	-
BD	-6.91	-8.36	-29.71	-
CD	8.83	6.20	13.67	-
A2	6.33	60.41	12.13	51.76
B2	8.13	31.97	28.06	-
D2	18.36	5.02	6.18	12.92

VII. Coefficients of the coded factors for each pulp suspension for velocities above V_{WT}.

Eucalypt pulp suspension:

$$\frac{\Delta H}{L} = \begin{aligned} &115.50 + 48.10\,Cons - 3007.98\,D_P + 26.61\,V \\ &-1817.31\,Cons \bullet D_P - 0.23\,Cons \bullet V - 162.26\,D_P \bullet V \\ &+34.15\,Cons^2 + 27091.14\,D_P^{\,2} + 2.23\,V^2 \end{aligned} \qquad (8)$$

$$Cons \in [0.84\%, 3.50\%];\; D_P \in [0.0381m, 0.1068m];\; V \in [0.60\,C^{1.21}\,{}^{m}\!/_{s}, 6.0\,{}^{m}\!/_{s}]$$

$$R^2_{adj} = 0.972$$

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

$$\frac{\Delta H}{L} = \begin{aligned} &109.38 + 11.48\,Cons - 3529.41\,D_P + 46.90\,V \\ &-203.13\,Cons \bullet D_P + 0.02\,Cons \bullet V - 384.42\,D_P \bullet V \\ &+9.17\,Cons^2 + 23785.36\,D_P^{\,2} + 1.22\,V^2 \end{aligned} \qquad (9)$$

$$Cons \in [0.90\%, 3.20\%];\; P_{Diameter} \in [0.0381m, 0.1068m];\; V \in [0.47\,C^{1.21}\,{}^{m}\!/_{s}, 6.0\,{}^{m}\!/_{s}]$$

$$R^2_{adj} = 0.957$$

Pine pulp suspension:

$$\frac{\Delta H}{L} = 23.69 - 44.60\,Cons + 7.17\,V - 3.21\,Cons \bullet V + 26.41\,Cons^2 + 2.55\,V^2 \qquad (10)$$

$$Cons \in [0.80\%, 3.60\%];\; V \in [0.38\,C^{1.86}\,{}^{m}\!/_{s}, 6.0\,{}^{m}\!/_{s}]$$

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

Ventura

Ferreira

Garcia

Rasteiro

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.

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;

D_P — internal pipe diameter;

$P_{Material}$ — pipe material;

R^2 — correlation coefficient;

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

V — bulk velocity;

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

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

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

α, β, γ — exponents, constants for a given pulp;

$\frac{\Delta H}{L}$ — friction head $\left({}^{mH_2O}\!/_{100m\ pipe} \right)$.

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