Flow and mixing behavior of low- and medium-consistency fiber suspensions downstream of a valve

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ABSTRACT: The flow behavior and mixing behavior of low-consistency (5%) and medium-consistency (8-14%) fiber suspensions in an expansion downstream of a ball valve have been studied. The flow coefficients for suspensions of 5 % and 8% consistency were found to be the same as that for water, indicating that the suspensions behaves as a Newtonian fluid and therefore could be considered "fluidized." The level of power dissipated per unit volume of the suspension also indicated fluidization. However, the quality of fiber-scale mixing in this zone for 8%-consistency pulp, measured by a tracer dye technique, was found to be only fair. For 13-14%-consistency pulp, the flow coefficient was less than for water, and it decreased with decreasing pressure drop, signifying that full fluidization had not taken place.

KEYWORDS: Flow, fluidization, low consistency, measurement, medium consistency, mixing, pulps, suspended solids, valves

Valves are used commonly in piping systems to control flow rates, pressures, and stock tank levels of fiber suspensions. Flow through a valve leads to a loss in head pressure because energy is dissipated at the valve. It is important to know this head loss for design purposes and for estimating the degree of mixing, since the energy dissipated at a valve is sometimes used for mixing.

Although the pertinent literature contains a substantial amount of information on friction loss in straight pipe sections (*1*), there is little published information on the flow behavior of fiber suspensions downstream of a valve (*2-4*). In one such study, Moller and Elmqvist measured the head loss for water and low-consistency (2-3%) fiber suspensions flowing through a gate valve (*2*). The head loss for pulps was greater than that for water, increasing approximately 20% for every 1% increase in consistency. Less information is available in the medium-consistency range (8-15%), which is growing in importance. Valves are commonly employed in this range to control flow and to achieve mixing. Consequently, studies of valve head losses in the medium-consistency range will provide better design data for pumping and for indirect estimation (*5*) of the degree of mixing.

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A specific example of medium-consistency valve mixing is the mixing of oxygen into medium-consistency (8-12%) pulp in oxidative extraction stages in pulp bleaching. This mixing is achieved typically by injecting oxygen through a porous sintered-metal sparger before a control valve (*6, 7*). The degree of mixing obtained is considered in some cases to be equivalent to that attained by high-intensity medium-consistency mixers (*8*). Consequently, mixing is accomplished at a substantial reduction in capital costs arising from the fact that the mill does not have to install a driven mixer. However, the exact degree of mixing produced has not been measured.

Only recently has the quality of mixing been measured directly in low-consistency fiber suspensions (*9*). Even more recently, a method has been developed for high-consistency (20-40%) fiber suspensions (*10*). In this latter study, the quality of mixing was characterized using measurements of a tracer dye concentration and Danckwerts's concept of intensity of segregation (*11*).

Our aims in this study are (a) to determine the flow characteristics of low- and medium-consistency fiber suspensions through a valve and (b) to measure fiber-scale mixing employing the technique developed earlier for high-consistency suspensions.

Experimental program

Overview

Flow behavior in a mill-scale valve was characterized by an effective flow coefficient, which was determined from pressure drop measurements for pulp and water. The flow coefficient is a measure of the irreversible losses from turbulent energy dissipation in

the valve. Therefore, it also provides a measure of the degree to which the pulp is "fluidized" in the valve.

Fluidization, described by Gullichsen and Harkonen (*12*), occurs when a fiber suspension is in a vigorous state of turbulence and as a result behaves as a liquid. The fluid motion at the valve can be used for mixing. The quality of such mixing at a valve was measured by a technique developed earlier to measure fiber-scale mixing in high-consistency pulp (*10*).

Flow loop

The measurements in this study were carried out on the medium-consistency flow loop in Paprican's Vancouver Laboratory. This recirculating flow loop consists of a stock tank, a medium-consistency centrifugal pump, a control valve, and a pipe loop with suitable instrumentation. Shown in **Figs. 1 and 2**, the loop includes:

Stock tank: 316L stainless steel, 1.2 m in diameter, 4.5 m high, a capacity of 5000 L (0.5 ton of o.d. pulp at 10% consistency), nozzles for dilution water and steam injection, a chemical injection nozzle at the pump inlet, and a residence time of 1-2 min.

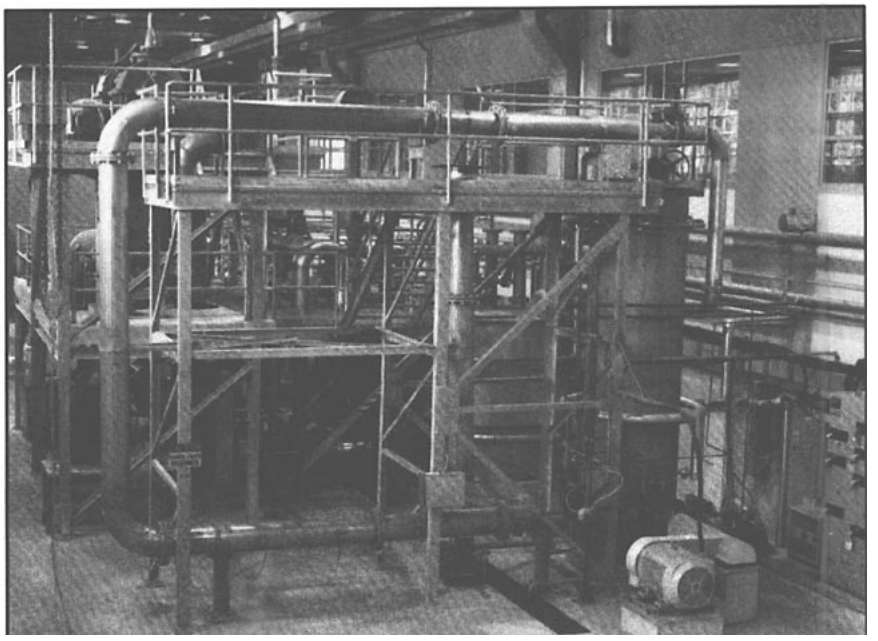
Pump: Kamyr centrifugal medium-consistency MC® Pump, Model MHL-10-P1 with degassing system, having a capacity of 600 tons/day at 10% consistency and a consistency range of 0-12%, using a 150-hp motor.

Pipe loop: 316L stainless steel, an initial 100-mm-diameter pipe section containing a magnetic flowmeter followed by a control valve and eccentric gradual expansion to a 300-mm-diameter pipe that can be arranged in a short loop (5 m) or a long loop (14 m), and a gate valve at the pipe loop discharge into the stock tank.

Valves: 316 stainless steel; a Neles PC03 control valve; an 80-mm-diameter, full bore ball valve; and a DeZurik Series L, 300-mm-diameter, knife-gate valve.

Instrumentation: magnetic flowmeter (Brooks Wafer-Mag, Rosemount Model 8711), pressure transmitters (Pressure Measuring Controls), temperature transmitter (Gordon Xac-Tohm resistance temperature detector), purged differential pressure level transmitter (Rosemount Model 1151DP), data acquisition and control (Bailey Network 90 distributed process control system).

1. Photograph of the medium-consistency flow loop located at Paprican's Vancouver Laboratory. Shown are the stock tank, the centrifugal medium-consistency pump, and the recirculating pipe loop.



The pipe loop was arranged in the long loop configuration shown in Fig. 2. The location of the pressure drop measurements is shown in **Fig. 3.** The measurements described here were for the pressure drop across the control valve and expansion which, for convenience, is called the "test section." This test section consisted of a sudden contraction, control valve, and eccentric gradual expansion (between B and C in Fig. 3). The flow rate was measured by the magnetic flowmeter located in the 100-mm-diameter pipe section (between A and B in Fig. 3) before the test section. The overall pressure drop, ΔP_{total}, was determined from the difference of the two gauge pressure measurements (between A and D in Fig. 3).

Experimental details

The effective flow coefficients for the test section were determined for water and the following fiber suspensions: fully bleached kraft at 5.5%, 8.3%, and 12.7-13.9% consistency and chemithermomechanical pulp (CTMP) at 8.2% consistency. The pressure drop, ΔP_{total}, was measured as a function of the control valve position and the flow rate.

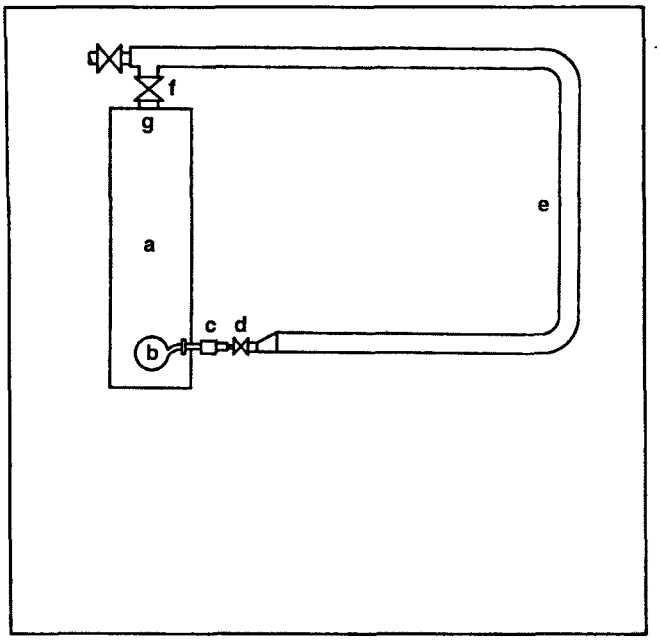
The flow rate for a fixed control valve position was varied by controlling the back pressure (the pressure downstream of the control valve) using the gate valve (f in Fig. 2). Increasing the back pressure by partially closing the gate valve decreased the pressure drop across the test section, resulting in a lower flow rate. Data were collected at 1-s intervals for 1 or 2 min for each flow condition.

The mixing experiment was performed using CTMP at 8.2% consistency. A tracer dye solution consisting of water and Astra Red P Liquid (Mobay, Bayer) was injected directly into the fiber suspension at the sudden contraction (E in Fig. 3) in the test section. The mixed pulp was collected at the discharge of the pipe loop (g in Fig. 2). The experimental conditions are summarized in **Table I.**

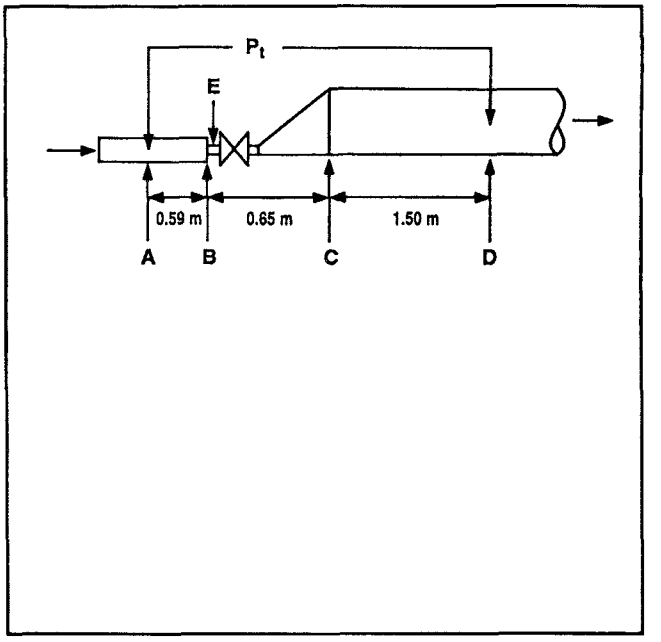
The distribution of dye in the mixing tests was measured, and the measurement was used to characterize the quality of mixing. The dye distribution was determined by selecting approximately 40 individual flocs from the pulp, each floc weighing about 10 mg. The flocs were obtained by subdividing five larger samples of pulp randomly selected from the mixed pulp.

The dye concentration for each floc was determined by placing the pulp sample in a test tube with 4 mL of glacial acetic acid. The solution was mixed well, was allowed to stand for

2. Diagram of the medium-consistency flow loop: (a) stock tank, (b) centrifugal medium-consistency pulp, (c) magnetic flowmeter, (d) control valve, (e) pipe loop, (f) gate valve, (g) pipe loop discharge into the stock tank



3. Locations of the pressure drop measurements. A-B indicates a 100-mm-diameter pipe section. B-C is the test section containing sudden contraction, the control valve, and eccentric gradual expansion. C-D is a 300-mm-diameter pipe section. The dye solution was injected at E.



I. Experimental conditions for the mixing experiment

Pulp (CTMP)	
Consistency, %	8.2
Flow rate, L/min	2830
Pressure upstream of valve, kPa	809
Pressure drop, kPa	709
Dye solution	
Concentration, g/L	0.25
Flow rate, L/min	2.0

15 min, and was centrifuged. The absorbances at 281 nm and 546 nm for the decanted solution were measured by a spectrophotometer (Perkin Elmer Lambda 4b ultraviolet/visible scanning spectrophotometer). The absorbance at 546 nm was due to the dye extracted from the pulp sample and therefore provided a measurement of the dye absorbed by the pulp sample during mixing. The absorbance at 281 nm was due to lignin extracted from the pulp sample and therefore provided a measurement of the lignin content. The remaining solution was filtered through a previously weighed glass-microfiber filter (Whatman). The pulp sample was dried in an oven, and its oven-dry mass was determined.

The dye concentration was determined from the ratio of the absorbances at 546 nm and 281 nm. The amount of dye absorbed by the pulp sample during mixing was proportional to the absorbance at 546 nm. Separate calibration experiments were performed to determine the proportionality constant for this relationship. The absorbance at 281 nm, which resulted from the lignin content of the pulp, was proportional to the pulp mass and therefore provided an indirect measurement of the pulp mass (*10*). The dye concentration was not calculated directly using the measured pulp mass since the pulp mass was small relative to the mass measurement errors.

This technique is extremely time consuming, which limited the amount of data that could be gathered. Therefore, only two tests were performed to characterize the distribution of dye in the pulp.

Data analysis

For subcritical (noncavitating) flow of liquids through a valve, the flow rate varies linearly with the square root of the pressure drop over the valve until incipient cavitation occurs. The flow rate, q, is given by (*13*):

$$q = F_p C_v \sqrt{\Delta P / G} \qquad (1)$$

where

F_p = piping geometry factor

C_v = valve flow coefficient

ΔP = pressure drop

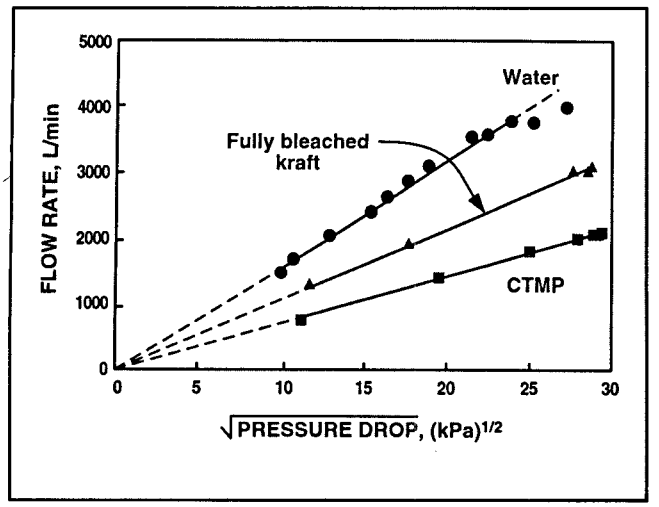
G = specific gravity of the liquid.

The valve flow coefficient accounts for the pressure drop due to the valve, and the piping geometry factor accounts for the pressure drop due to contraction and expansion. The term F_pC_v is the effective flow coefficient for the test section.

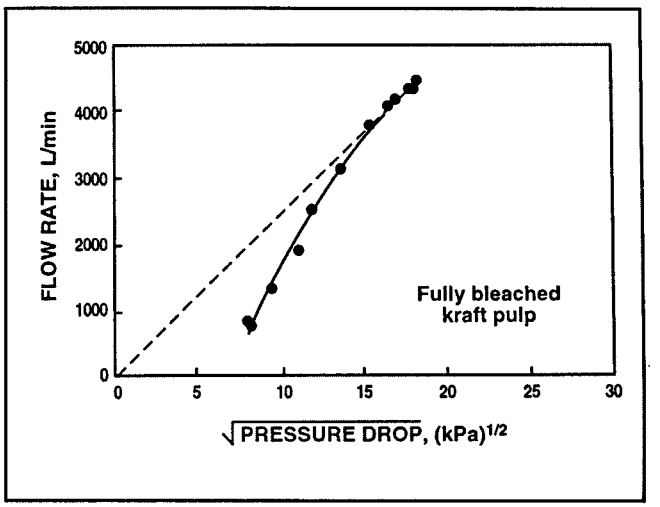
The overall pressure drop, ΔP_{total}, resulted from the energy dissipation over the test section (ΔP, between B and C in Fig. 3) and the wall friction losses in the pipe sections between the pressure transmitters and the test section (between A and B and between C and D in Fig. 3). For water, these friction losses were negligible, and the pressure drop resulting from the test section alone was given by the overall pressure drop. For fiber suspensions, the pipe friction losses were much larger than for water.

The pressure drop for the test section alone, ΔP, was calculated by subtracting the friction losses in the pipe sections from the overall pressure drop using a friction loss per unit length measured in the 300-mm-

4. Flow rate vs. square root of the pressure drop across the test section for water (50% valve position), fully bleached kraft pulp (5.5% consistency, 40% valve position), and CTMP (8.2% consistency, 30% valve position)



5. Flow rate vs. square root of the pressure drop across the test section for fully bleached kraft pulp, 13.5% consistency, at 70% valve position



diameter pipe section downstream of the pressure transmitter indicated as D in Fig. 3. This friction loss was corrected for the 100-mm-diameter pipe section using the diameter dependence given by Bodenheimer (*14*). The pressure drops caused by friction in the pipe sections ranged from 3 kPa to 21 kPa (0.3–7.5% of overall pressure drop) for fiber suspensions up to 8% consistency. For the fiber suspensions of 13–14% consistency, the pressure drops caused by friction in the pipe sections ranged from 30 kPa to 68 kPa.

The quality of fiber-scale mixing was characterized by the intensity of segregation, I, defined as the root mean square of the normalized dye concentration (*9*, *15*):

$$I^2 = \frac{\sum_{i=1}^{n}(a_i - \bar{a})^2}{n\bar{a}^2} \qquad (2)$$

where

a_i = dye concentration for floc i

$\bar{a}$ = average dye concentration.

Good fiber-scale mixing is indicated by a small intensity of segregation.

Results and discussion

Flow experiment

Figure 4 presents typical pressure drop measurements shown as the flow rate plotted against the square root of the pressure drop across the test section for water and for fiber suspensions up to 8% consistency. As shown, the flow rate varied linearly with the square root of the pressure drop for both water and pulp for small pressure drops that resulted when back pressure was applied by partially closing the gate valve.

For some cases of large control valve openings, such as for water with the control valve at the 50% position, the relationship between the flow rate and the square root of the pressure drop deviated from linearity for large pressure drops that resulted when back pressure was not applied—i.e., when the gate valve was fully opened. This deviation from linearity indicated incipient cavitation.

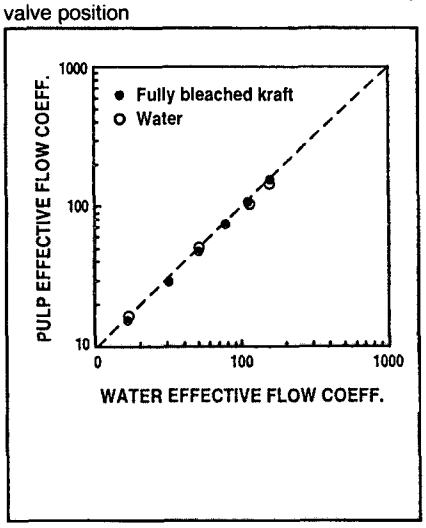
In **Fig. 5**, the flow rate is plotted against the square root of the pressure drop across the test section for fully bleached kraft at 13.5% consistency. For large pressure drops, the flow rate varied linearly with the square root of the pressure drop, as was observed for water and for fiber suspensions at lower consistency. For lower pressure drops, below about 200 kPa, the relationship between the flow rate and the square root of the pressure drop deviated from linearity. Plugging occurred at the valve when the pressure drop was reduced to about 50 kPa.

The effective flow coefficient was calculated using Eq. 1 from measurements when the flow rate varied linearly with the square root of the pressure drop across the test section. The specific gravity for water was determined for its operating temperature. The bulk density of pulp was estimated from its consistency under the assumption that the fiber density was 1.5 gm/cm^3 (*16*). For pulp, F_pC_v was also calculated from measurements when back pressure was not applied.

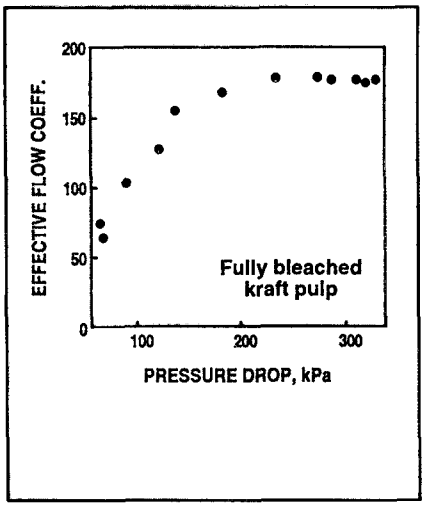
The effective flow coefficient for fiber suspensions up to 8% consistency was essentially the same as that of water. **Figure 6** illustrates this linearity for fully bleached kraft at 5.5% consistency. In this figure, F_pC_v for pulp is plotted against the effective flow coefficient for water at the corresponding control valve position. On average, F_pC_v for pulp when back pressure was applied was 0.98 times that of water. When back pressure was not applied, the measured F_pC_v for pulp for large valve openings was less than those values measured for both water and pulp with back pressure applied as a result of incipient cavitation. Similar results were obtained for fully bleached kraft at 8.3% consistency and CTMP at 8.2% consistency with the effective flow coefficient for pulp averaging 0.98 times that of water for fully bleached kraft and 0.99 times that of water for CTMP.

Our finding that the effective flow coefficients for 5%- and 8%-consistency fiber suspensions are similar to those for water for large pressure drops (120–950 kPa) may be compared to previous results at low consistencies. Moller and Elmqvist (*2*) observed that the flow coefficients for 2–3%-consistency pulp flowing through a

6. Effective flow coefficient for fully bleached kraft, 5.5% consistency, measured with and without back pressure vs. the effective flow coefficient for water at the corresponding valve position



7. Effective flow coefficient vs. pressure drop across the test section for fully bleached kraft, 13.5% consistency, at 70% valve position



gate valve were less than those for water. However, their measurements were performed for small pressure drops (1-100 kPa). Robbins reported that the flow coefficients for 2-5%-consistency pulp flowing through a ball valve depended on consistency and pressure drop (*3*). For small pressure drops, he found that flow coefficients for pulp were less than those for water, which is similar to the findings of Moller and Elmqvist (*2*). The flow coefficient decreased with increasing consistency and decreasing pressure drop. For large pressure drops, he found that flow coefficients for pulp were the same as those for water, which is similar to our findings.

In **Fig. 7**, the effective flow coefficient for fully bleached kraft at 13.5% consistency is plotted against the pressure drop across the test section. For large pressure drops, the effective flow coefficient was independent of pressure drop. For small pressure drops, below about 200 kPa, F_pC_v decreased with decreasing pressure drop. This finding is similar to those of Robbins for a ball valve at low consistency (*3*), Kivipeffo for a segment valve at medium consistency (*4*), and Andrews and Husu for ball, segment, and butterfly valves (*17*).

In **Fig. 8**, the effective flow coefficient for fully bleached kraft at 12.7-13.9% consistency is plotted against F_pC_v for water at the corresponding control valve positions. The results are shown for measurements with back pressure applied. The results for pulp were calculated for large ΔP where F_pC_v was independent of pressure drop. On average, the effective flow coefficient for pulp was 0.93 times that of water.

The degree to which fiber suspensions behave as a fluid—i.e., the degree of fluidization—can be gauged from the degree that the pressure drop compares to water. At rest, fiber suspensions form fairly stable networks that can only be disrupted when subjected to sufficient shear stress (*12*). The pulp network strength depends on the fiber suspension consistency (*18*). When the network is disrupted, to the extent that fibers and flocs move relative to one another, the pulp then has liquid-like properties and can be considered fluidized. The similarity of the flow behavior of pulp to that of water indicates that the pulp behaved as a fluid in the control valve—i.e., it was fluidized. Pressure drop behavior indicating fluidization occurred for all observed pressure drops (120-950 kPa) across the test section for 5%- and 8%-consistency fiber suspensions and for pressure drops greater than about 200 kPa for fiber suspensions of 13-14% consistency.

Other evidence that the pulp was fluidized by the control valve comes from the estimate of the power dissipated per unit volume, which reflects the level of small-scale motion (*5*). The exact volume over which dissipation takes place is uncertain, but a lower limit for the power per unit volume can be estimated by assuming that the power was dissipated uniformly over the section for the control valve and expansion (between B and C in Fig. 3). For the conditions of Table I, the power dissipated was 33 kW. This yields a lower limit for the power per unit volume of 2.7 MW/m^3. The upper limit for the power per unit volume, assuming that the power was dissipated solely in the valve, was 35 MW/m^3.

These power values may be compared to findings of other work in which power dissipation was measured for observed levels of fiber suspension fluidization. Bennington *et al.* (*5*) found the power required to fluidize an 8%-consistency fiber suspension to be 0.27 MW/m^3, much less than the power dissipated by the control valve. Also, our measured power dissipations are comparable to the power dissipation range (1.8-110 MW/m^3) reported in medium-consistency pumps and high-intensity, medium-consistency mixers that fluidize fiber suspensions (*5*). In summary, our measured power dissipations indicate that the pulp was fluidized at the valve.

The flow behavior of 13-14%-consistency fiber suspensions differed from that for water when the pressure drop was below about 200 kPa—that is, it was not fluidized. This finding suggests that insufficient power was dissipated by the control valve to disrupt the fiber networks. The power required to fluidize a 13%-consistency fiber suspension is estimated to be about 10 times that for an 8%-consistency pulp using data from Bennington *et al.* (*5*). For pressure drops greater than 200 kPa, the flow behavior of 13-14%-consistency pulp was similar to that for water, indicating fluidization.

Mixing experiment

The quality of mixing can be estimated from the energy dissipation at the valve. As discussed, the power dissipation per unit volume was comparable to that reported for high-intensity, medium-consistency mixers. However, while the power dissipation per unit volume indicates the rate of mixing, the energy expenditure indicates the extent of mixing (*5*). The energy expenditure during the valve mixing experiment was 8.6 kJ/kg, which is approximately half the

energy expenditure of some high-intensity, mechanical, medium-consistency mixers (*5*). This suggests that the degree of mixing achieved by the valve is less than that achieved by high-intensity mixers.

The results of our tracer dye measurements are given in **Table II**. The quality of mixing was characterized by the measured intensity of segregation, which was found to be 0.25 and 0.14 for the two tests conducted under the same conditions. The magnitude of these values and the difference between them gives us some direct, though limited, information on mixing.

First, there was a significant difference (with 99% confidence) between the two values of the intensity of segregation. This difference is similar in magnitude to previous measurements of fiber-scale mixing in mill chlorination mixers (*15*). These variations were attibuted to unsteady operating conditions and poor macro-scale mixing. In our case, it is more likely that the latter occurred—that is, the dye was not well distributed over a scale of the pipe diameter where it was injected. This hypothesis is supported by visual observation. The mixed pulp was not uniform in color. It was predominantly light pink with areas of darker pinks and brown, indicating variations in macro-scale mixing.

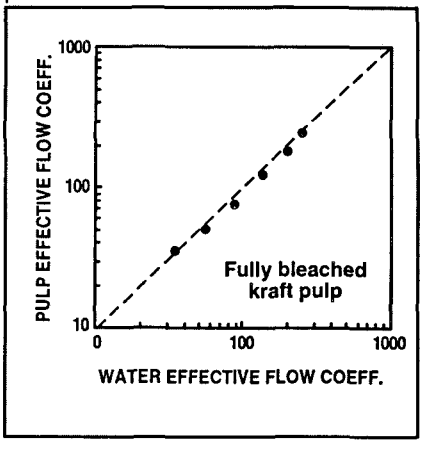
The average magnitude of I provides information on the quality of fiber-scale mixing. The average intensity of segregation for the mixing experiment, given by the root mean square of the intensities of segregation for the two tests, was 0.21. This value can be compared with I measured for low-consistency mixing in mill chlorination units and high-consistency mixing in a Frotapulper. The former, for low-consistency (2-4%) mixing by in-line static mixers or continuous stirred tanks, ranged from 0.07 to 0.16 (*15*) and for very bad laboratory mixing to 0.67 (*9*). For high-consistency (27%) mixing by a Frotapulper, I ranged from 0.27 to 0.45 and for bad laboratory mixing ranged from 1.15 to 1.48 (*10*).

Thus, by comparison of I values, fiber-scale mixing at the valve was poorer than that observed in low-consistency chlorination units but was better than that obtained in high-consistency mixing by a Frotapulper. This result is consistent with the observation that the quality of fiber-scale mixing in mill chlorination units became poorer as the consistency increased (*15*).

Our findings have some direct implications for the quality of mixing obtained in oxidative extraction stages, where virtually the same valve and flow arrangement exists as in our experimental setup. It has been established that by use of a gas sparger injector before the control valve, satisfactory mixing can be achieved (*7, 8*). This mixing is thought to come from residual decaying turbulence at the pump discharge and/or from the mixing action of the valve.

Previous findings on the reflocculation time of fiber suspensions in decaying turbulence (*18*) suggest that little turbulence remains past the pump discharge. While we cannot confirm this here, our findings suggest that the pulp is refluidized in the valve and expansion and that the resultant degree of mixing created by this flow is about half that of a high-intensity mechanical mixer. However, the quality of mixing achieved may or may not be equal, depending upon the "mixing load" imposed by the injection arrangement. Mixing load, defined by Bennington *et al.* (*5*), reflects the amount of mixing needed, in this case, to disperse the gas into bubbles and transport it over the distance necessary for complete mixing. While this may be low in a gas sparger system in a small-diameter pipe (100-150 mm), it may be larger or smaller in dynamic high-intensity mixers.

8. Effective flow coefficient for fully bleached kraft, 12.7-13.9% consistency, measured with back pressure applied vs. the effective flow coefficient for water at the corresponding valve position



11. Measured intensity of segregation for the mixing experiment

	Test 1	*Test 2*
Number of flocs	44	34
Mean floc mass, mg	10.4	7.3
Mean dye conc., mg/g fiber	0.23	0.24
Intensity of segregation	0.25	0.14

Summary and conclusions

The effective flow coefficient for fiber suspensions up to 8% consistency in a valve and subsequent expansion was found to be the same as that for water, independent of pulp type or consistency for pressure drops greater than 120 kPa across the test section. This similarity suggests that the pulp has fluid-like behavior, or that it is fluidized. The measured power dissipation per unit volume for the fiber suspension falls in the range measured in previous work in which fluidization was observed; therefore, this result supports the concept that fluidization takes place.

The effective flow coefficient for 13-14% fiber suspensions was less than that for water. Also, the effective flow coefficient decreased with decreasing pressure drop across the test section for pressure drops less than about 200 kPa. This finding suggests that the fiber suspensions were not fluidized for these low pressure drops. On the other hand, for pressure drops greater than 200 kPa, the flow behavior of fiber suspensions of 13-14% consistency was similar to that for water, indicating fluidization.

Measurements of fiber-scale mixing for 8%-consistency pulp showed that mixing quality was poorer than that observed in earlier measurements of mixing in low-consistency chlorination but was better than that for high-consistency mixing by a Frotapulper. The energy expended on the pulp was approximately half that expended in a high-intensity mechanical mixer. Thus, the degree of mixing

achieved, while significant, is likely to be less than that in high-intensity mixers. The actual quality of mixing, however, will also depend on the mixing load imposed by the gas injection system.

Literature cited

1. TAPPI TIS 0410-12 "Pipe friction pressure loss of fiber suspensions: literature review and evaluation of data and design methods" (1985).
2. Moller, K. and Elmqvist, G., Tappi 63(3): 101(1980).
3. Robbins, W., Proceedings of the 1984 ISA International Conference, Instrument Society of America, Research Triangle Park, NC, Vol. 39, p. 105.
4. Kivipeffo, P., Paper 210(2): 32(1988).
5. Bennington, C.P.J., Kerekes, R. J., and Grace, J. R., J. Pulp Paper Sci. 15(5): J186(1989).
6. Greenwood, B. F. and Harkonen, E., 1986 Engineering Conference Proceedings, Book 2, TAPPI PRESS, Atlanta, p. 571.
7. Pageau, G. L. and Mowbray, F. A., Tech. Sect. CPPA 74th Annual Meeting Preprints, CPPA, Montreal, 1988, p. A183.
8. Circucci, J. F., Costa, D. S., Manzi, D., *et al.*, 1987 International Oxygen Delignification Conference, TAPPI PRESS, Atlanta, p. 81.
9. Paterson, A.H.J. and Kerekes, R. J., J. Pulp Paper Sci. 11(4): J108(1985).
10. Francis, D. W. and Kerekes, R. J., J. Pulp Paper Sci. 16(4): J130(1990).
11. Dankwerts, P. V., Appl. Sci. Res., Sect. A, 3: 279(1953).
12. Gullichsen, J. and Harkonen, E., Tappi 64(6): 69(1981).
13. Flow equations for sizing control valves, ANSI/ISA Standard S75.01 (1985).
14. Bodenheimer, V. B., Southern Pulp Paper Manufacturer 32(9): 42(1969).
15. Paterson, A.H.J. and Kerekes, R. J., J. Pulp Paper Sci. 12(3): J78(1986).
16. Parham, R. A., Pulp and Paper Manufacture, Vol. 1, 3rd edn. (M. J. Kocurek and F. Stevens, Ed.), TAPPI PRESS, Atlanta, 1983, p. 50.
17. Andrews, E. and Husu, M., Tappi J. 76(6): 86(1991).
18. Kerekes, R. J., Soszynski, R. M., and Tam Doo, P. A., The flocculation of fibers: their interaction with the production process and their effect on paper properties, *in* Papermaking Raw Materials, Vol. 1, p. 265, Trans. Eighth Fundamental Research Symposium, held at Oxford, Sept. 1985, Mechanical Engineering Publications, Fundamental Research Committee, (ISBN 0 85298 5797).

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