PEER REVIEWED

Fractionation of softwood TMP by flotation

WILLIAM F. ECKERT, JACOB H. MASLIYAH, AND ARTIN AFACAN

ABSTRACT

A laboratory flotation cell was used to achieve fractionation of 100% softwood thermomechanical pulp on the basis of fiber length. At a consistency of 0.24%, 75–80 wt.% of the fibers in the cell that were 1.5 mm in length or longer were captured in the froth and removed from the cell, while less than 50 wt.% of the fibers shorter than 1.5 mm were captured by the froth. The initial pulp had a length-weighted average length of 1.39 mm, while the remaining pulp in the cell had an average length of 0.69 mm.

Application:

A possible application for this process is the recovery of valuable long fibers from mechanical or recycled pulps.

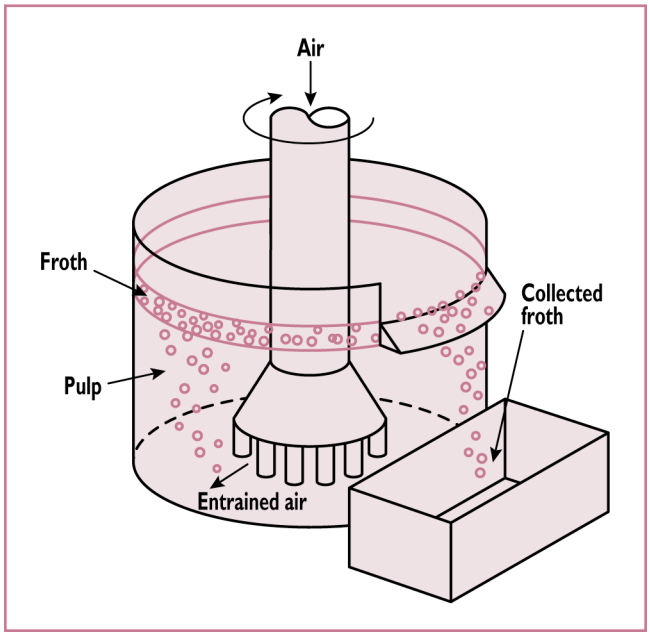
THE FRACTIONATION OF A PULP into two or more streams on the basis of fiber length has been a long-sought-after process. Moller *et al. (1)* outlined a number of possible justifications for the fractionation of pulp: (a) the optimization of multi-ply paper and board by separating the pulp into a different fiber length stream for each layer, (b) the production of different paper products by fractionating one pulp into separate feed streams for multiple paper machines, (c) the conservation of energy, by only refining or beating each fraction of a pulp as is needed, and then recombining the fractions for one furnish, and (d) the extraction of the most valuable fibers from recycled paper.

Note that Bliss *(2)* found that a number of mills had experimented with fractionation as a method of energy conservation, but these mills had abandoned this approach due to little or no savings. In the future, the increased recycling of paper products will certainly increase the justification for fractionation of secondary fiber. Also, at the present time, there are shortages of virgin fiber in many areas, thereby increasing pressure on industry to move away from chemical pulping processes to mechanical pulping processes with higher yields [40–55% vs. 85–95% by weight per Smook *(3)*].

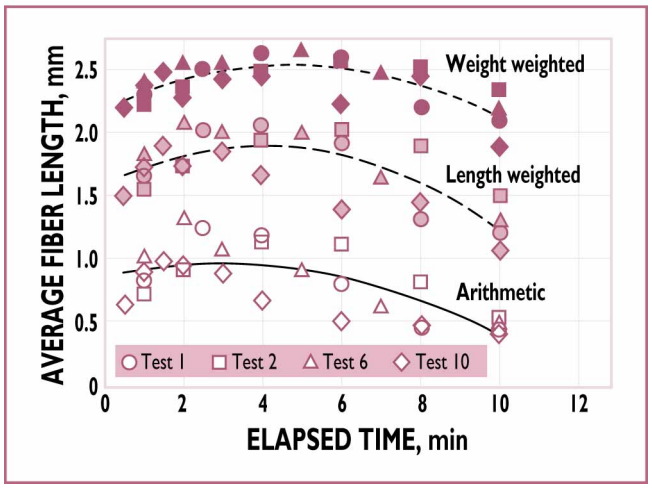
Although the mechanical pulping technique extracts more pulp from the same amount of wood than the chemical pulping technique, the former tends to produce a wider fiber length distribution due to a tearing of fibers. Fractionation on the basis of length may allow a mechanical pulp to be separated into several grades, increasing its economic value. Rewatkar and Masliyah *(4)* reviewed wood pulp fractionation and listed a number of possible fractionation devices, such as the plate atomizing wheel, hydrocyclone, pressure screen, Johnson fractionator, and Jacquelin apparatus. To date, these devices have not been widely used in the paper industry, possibly for two reasons. First, for many of these devices, the primary parameter that controls fractionation is not the fiber length, but other parameters, such as fiber specific volume or specific surface, fiber diameter, and wall thickness. Second, in many cases, the capital cost of installing mill-scale equipment and the amount of energy consumed in fiber fractionation negate the potential economic benefits.

The objective of this study was to fractionate a mechanical pulp into two fiber streams on the basis of fiber length using a flotation process. A Wemco Fagergren laboratory flotation cell was used to fractionate 100% softwood thermomechanical pulp (TMP) at consistencies of 0.24%, 0.46%, and 0.83%. A semi-batch process was used. The cell was initially charged with a volume of pulp slurry. During the experimental runs, the formed froth overflowed and was manually scooped from the cell, carrying with it a portion of pulp. Samples of the initial pulp, the froth overflow at various time intervals, and the final pulp in the cell were analyzed for fiber length distribution and pulp consistency. At low pulp consistencies, excellent separation of the longer fibers from the shorter fibers in softwood TMP was achieved. The froth that was removed from the cell had a significantly longer average fiber length than that of the original pulp. As well, the remaining pulp tailings in the cell at the end of the experimental run had a substantially shorter average fiber length than that of the original pulp.

In 1995, Li and Muvundamina *(5)* published results for fiber fractionation using froth flotation. They specifically studied the separation of chemical and mechanical pulps; however, they noted that some fractionation occurred on the basis of length. They found that the chemical pulps with low lignin content floated more freely than the mechanical pulps. They believed that the surfactant was adsorbed by the lignin present on the mechanical pulp, thus increasing its wettability over that of the chemical pulp. They attributed the preferential flotation of the chemical pulp to this difference in surface activity. However, they used a mixture of two pulps with very different average lengths.



1. Wemco Fagergren flotation cell



2. Variation over time of the average fiber length in the froth (C_m = 0.24% without additive)

The mechanical pulp (groundwood) and chemical pulp (bleached pulp) had weight-weighted average lengths of 0.70 mm and 2.90 mm, respectively [see Li and Muvundamina *(6)*].

In contrast, the present study used a single TMP pulp with a weight-weighted average length of 2.15 mm, and fractionation still occurred at lower consistencies. The flotation fractionation results reported by Li and Muvundamina are consistent with those of the present study. We believe that the primary mechanism of fractionation is mechanical entrainment and capture of the longer fibers in the froth rather than surface activity of the fibers.

EXPERIMENTAL METHOD

The laboratory cell used in this study was a self-aerating mechanical type, specifically a Wemco Fagergren model (see **Fig. 1**). It was initially filled with a well-mixed pulp slurry. The volume used was 2.75 L of pulp without an additive and 2.50 L of pulp when using an additive. The additive was 0.1 mL of pine oil, which acted as a frother. A small sample of the initial pulp was taken and set aside before each run. The motor was turned on with the suction-side air valve closed for 30 seconds to allow mixing of the pulp and frother. The air valve was then opened fully to aerate the pulp slurry, resulting in the formation of a froth. The froth was scraped from the cell into overflow pans, with the pans being replaced at timed intervals.

Normally, for the first few minutes of a run, the pans were replaced every 30 seconds because of the large amount of froth produced. As a run progressed, the froth production rate decreased, and the intervals were progressively lengthened to 1 and then 2 min. The total run time for each test was 10–13 min. During an experimental run, water was added to the flotation cell to maintain the slurry level at its original value and to wash down any fibers that adhered to the cell wall above the liquid level. After the allotted time, the motor was turned off, and the weight of the remaining pulp slurry in the cell was measured. The weights of the froth collected in the various time intervals were also measured. Samples of the initial and final pulp in the cell, and from each of the froth pans, were analyzed using an OpTest Fiber Quality Analyzer to determine fiber length distribution. Finally, the samples were filtered and dried to determine the pulp consistency.

RESULTS AND DISCUSSION

Table I lists the arithmetic, length-weighted, and weight-weighted average fiber lengths, and the percentage of fines for the initial and final pulp in the cell. Note that in this study, fines were defined as any particles less than 0.2 mm in length. The results are split into four groups:

- The first group had a pulp consistency (C_m) of 0.24% with no additives.
- The second group had the same pulp consistency (0.24%) but with pine oil added as a frother.
- The third group had a pulp consistency of 0.46% with pine oil.
- The fourth group had a pulp consistency of 0.83%, also with pine oil.

The first group of tests without an additive produced some froth, as the pulp slurries contained small amounts of natural surfactants. As can be observed from Table I, the average fiber lengths of the final pulp without an additive were only slightly shorter than the original pulp. Also, the arithmetic percentage of fines left in the cell was about 42% vs. 40% initially. On this basis, the fractionation of pulp by flotation without an additive is not a commercially viable process. However, the addition of a small amount of frother (pine oil) changed the results considerably, as shown in Table I.

Test no.	Average fiber length, mm		Length-weighted average, mm		Weight-weighted average, mm		Fines <0.2 mm, %	
	Initial	Final	Initial	Final	Initial	Final	Initial	Final
100% TMP softwood; C_m=0.24% with no additives								
1	0.59	0.52	1.37	1.24	2.12	1.98	36.75	41.90
2	0.59	0.50	1.40	1.22	2.11	1.97	39.95	43.65
6	0.58	0.54	1.39	1.32	2.15	2.09	38.73	40.02
10	0.55	0.54	1.39	1.31	2.19	2.05	42.40	41.75
100% TMP softwood; C_m=0.24% with pine oil								
4	0.54	0.30	1.38	0.63	2.19	1.28	43.73	54.99
8	0.60	0.31	1.43	0.64	2.19	1.29	39.02	54.05
9	0.56	0.33	1.35	0.71	2.08	1.37	41.52	51.73
11	0.55	0.38	1.39	0.89	2.19	1.62	42.40	48.90
13	0.60	0.29	1.46	0.56	2.26	1.07	38.23	54.73
100% TMP softwood; C_m=0.46% with pine oil								
12	0.55	0.43	1.36	1.09	2.12	1.96	41.92	46.12
14	0.60	0.38	1.42	0.95	2.19	1.80	38.55	49.83
100% TMP softwood; C_m=0.83% with pine oil								
15	0.56	0.58	1.29	1.38	2.01	2.12	39.75	38.33
16	0.59	0.58	1.39	1.37	2.15	2.16	38.17	38.17

I. Properties of initial and final pulp in flotation cell

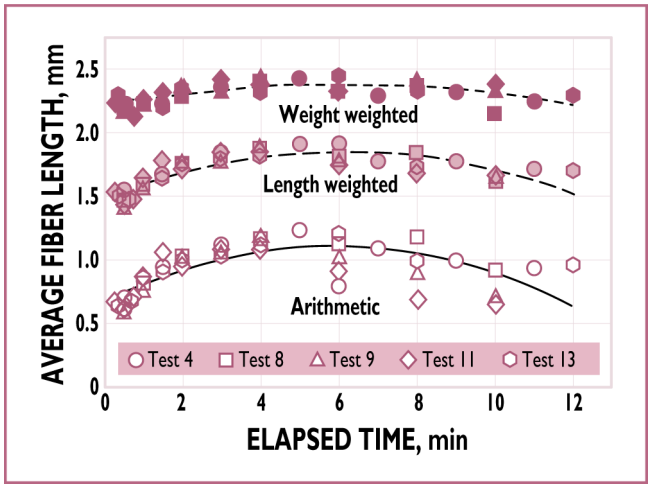
The tests with a pulp consistency of 0.24% and pine oil show a considerable difference between the average fiber lengths of the initial and final pulp in the cell. As well, the percentage of fines left in the cell was considerably higher (about 53%) than the initial value. This indicates that a significant proportion of the long fiber was captured by the froth and removed from the pulp slurry in the cell.

The third group of tests had the same volume of frother added to a higher pulp consistency of 0.46%. The final pulp in the cell was shorter than the initial pulp, but the results were not as dramatic as those with a pulp consistency of 0.24%. For instance, the initial length-weighted average of the pulp in the cell was approximately 1.40 mm, and the final average was about 1.00 mm. In comparison, the pulp at a consistency of 0.24% had a final length-weighted average in the cell of about 0.69 mm. The percentage of fines remaining in the cell at the end of a run averaged 48%.

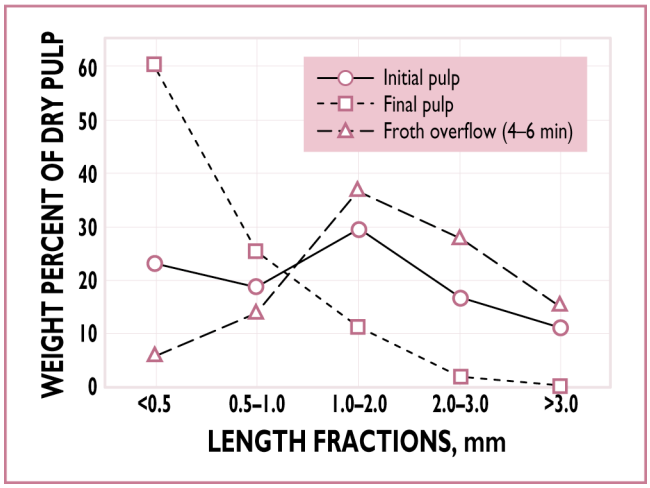
For the fourth set of tests, a higher pulp consistency (0.83%) was used. There was little difference in the fiber length distribution between the initial and final pulp samples. The arithmetic, length-weighted, and weight-weighted average fiber lengths for the froth overflow from the cell corresponding to the first group of tests in Table I are given in **Fig. 2.** The average fiber length of the pulp captured in the froth was a function of time. Note that the data for a froth sample collected during a time interval were plotted at the end of that time interval. For instance, the average lengths shown at 10 min in Fig. 2 are for the froth collected during the 8–10-min interval of the tests. In Fig. 2, the length-weighted average length of the froth was higher than the pulp in the cell at the start of the tests. However, near the end of the tests, the froth production was very low, and the average length of fiber in the froth was slightly lower than the initial pulp. As well, the data for the four tests in this first group had quite a bit of scatter. This indicates that the froth production, and hence the fractionation, was very dependent on the concentration of natural surfactant in a particular batch.

Figure 3 shows the variation of average fiber length in the froth over time for pulp with consistency of 0.24% with the pine oil additive. Comparing the length-weighted averages of the fibers in Figs. 2 and 3, we observed that there was much less scatter in the results when the frother was used. The average fiber lengths captured in the froth were always higher than the initial values during a test. The longest fiber lengths were collected during the 4–8-min interval of a run. Specifically, for test 13, the fiber captured in the froth at the midpoint of the run had an arithmetic average length of 1.21 mm, a length- weighted average of 1.91 mm, and a weight-weighted average of 2.45 mm. The corresponding average lengths for the initial pulp were 0.57, 1.39, and 2.15 mm, respectively.

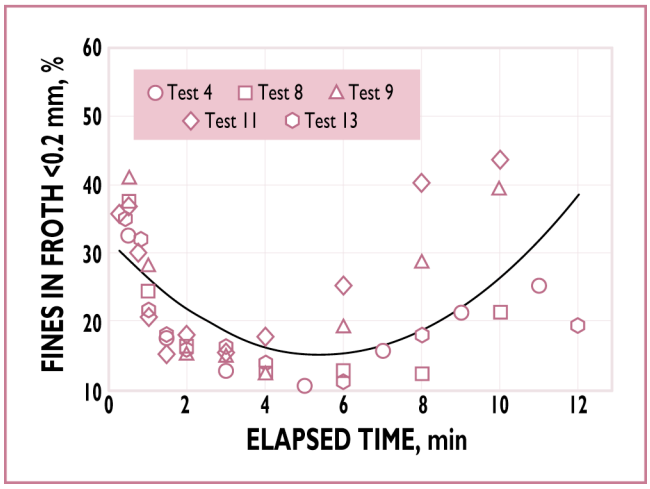
The distribution of fiber lengths in the initial pulp, final pulp, and that



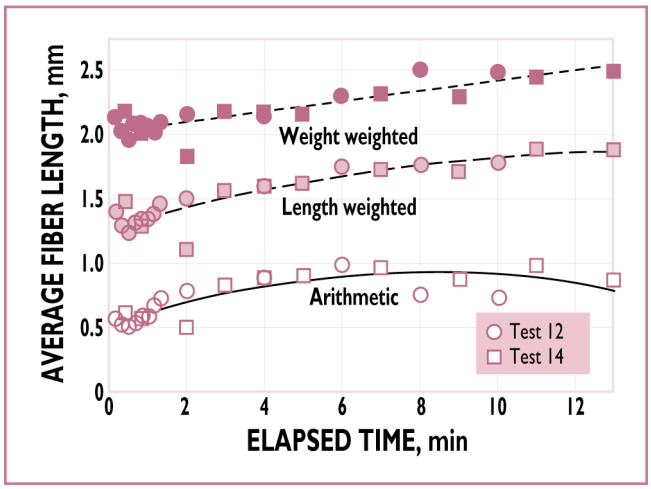
3. Variation over time of the average fiber length in the froth (C_m = 0.24% with pine oil)



4. Fiber distributions for test 13 (C_m = 0.24% with pine oil)



5. Variation over time of the percentage of fines in the froth overflow (C_m = 0.24% with pine oil)

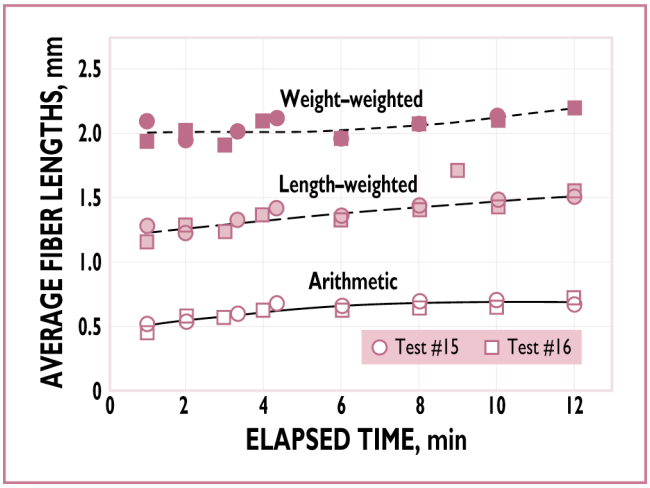


6. Variation over time of the average fiber length in the froth (C_m = 0.46% with pine oil)

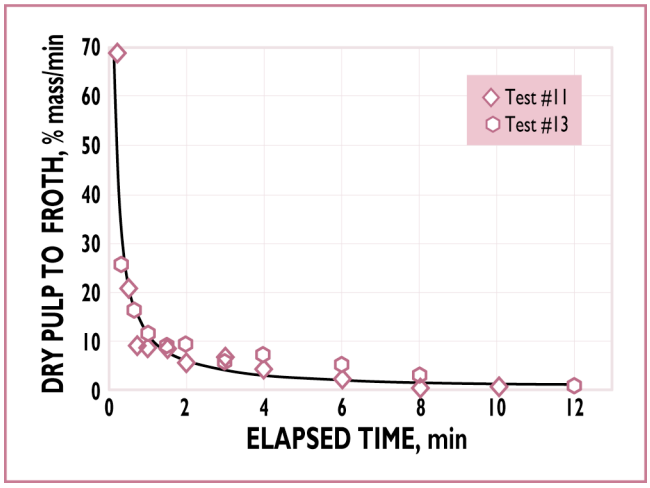
captured in the froth were also considerably different. A comparison of the weight percentages of the various fiber length fractions for test 13 is shown in **Fig. 4**. In the initial pulp, 23% of the dry weight of the fiber was less than 0.5 mm in length, while 30% was 1–2 mm in length. In the captured froth, only 6% of the fiber weight was less than 0.5 mm, and 37% was 1–2 mm in length. The pulp remaining in the cell at the end of the test had a much narrower distribution, with 60% of the fiber weight being less than 0.5 mm and 11% being 1–2 mm in length.

Figure 5 shows the variation over time of the arithmetic percentage of fines captured by the froth for the second group of tests (C_m = 0.24% with pine oil). At the start of a run, the froth contained 40% fines, which was about the same as the initial pulp. Then, the amount of fines steadily decreased to a minimum of 10–15% at the 4–6-min time interval. Toward the end of the run, the fines in the froth again rose to a value close to that of the original pulp. As expected, the amount of fines present in the froth over a test run was inversely proportional to the average length of the fibers captured in the froth.

Our results show that a significant variation in the length distribution of the fibers and amount of fines captured in a froth occurred with time. This can be explained by the variation in concentration of surfactant (pine oil) in the cell. At the start of a test, the concentration of surfactant was highest, and a large volume of froth was generated—so much so, that the froth naturally overflowed the cell without assistance. As a test progressed, the surfactant concentration in the cell decreased, because the surfactant was removed from the cell with the froth and because of the addition of clean water. Typically, 1–2 min into the test, the surfactant concentration had decreased sufficiently that only a moderate amount



7. Variation over time of the average fiber length in the froth (C_m = 0.83% with pine oil)



8. Variation over time of the recovery of fiber mass in the froth (C_m = 0.24% with pine oil)

of froth was being generated, and manual removal of the froth was required. In the final few minutes of a test, the surfactant concentration was quite low, and the froth layer that was generated was quite thin. Because this thin layer was manually removed with a scraper, a small portion of the pulp slurry was carried with it; therefore, the fiber length distribution in the froth was much closer to that in the cell.

Figure 6 shows the variation over time of the average lengths of the fiber captured by the froth for a pulp consistency of 0.46%. This figure, along with the initial and final values shown in Table I, indicates that the flotation process was less effective at separating the long fibers from the pulp slurry than when using pulp of 0.24% consistency. The length-weighted and weight-weighted average lengths increased steadily during the run time, while the arithmetic average decreased slightly near the end of the test runs. The increase in fractionation in the latter half of the test runs was probably due to the addition of water, thereby decreasing the pulp consistency in the cell. For both tests 12 and 14, the consistency of the pulp remaining in the cell was 0.18%.

The variation over time of the average lengths of the fiber in the froth overflow for a pulp consistency of 0.83% is shown in **Fig. 7**. The average length of fiber in the froth was less than the initial pulp for the first few minutes of a run, and then higher than the initial value for the last few minutes of a run. Very little fractionation of the pulp into longer and shorter fractions occurred at this pulp consistency. It appears that there is an upper limit in pulp consistency, above which fractionation by flotation will not work.

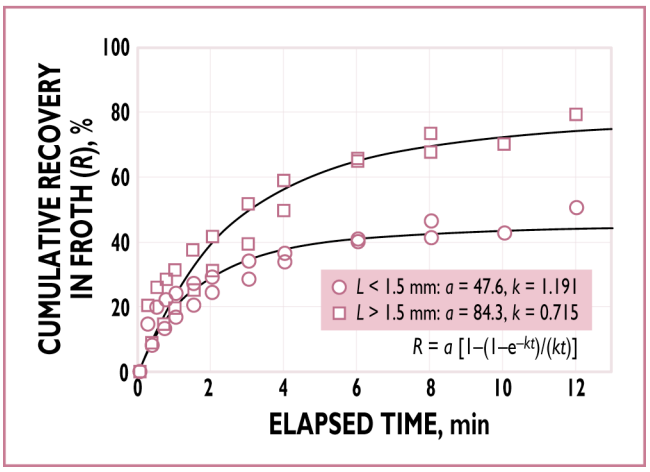
These results demonstrate that pulp consistency has an effect on fractionation performance. The higher the pulp consistency, the lower is the effectiveness of fractionation by the flotation process. This may be explained by relating the consistency of the pulp to the crowding factor, N [Kerekes and Schell *(7)*]. The crowding factor can be considered a measure of the intimacy of fiber-to-fiber contact. Kerekes and Schell characterized the fiber contact regimes as follows:

- For $N < 1$, the suspension is considered dilute, with chance fiber contact.
- For $1 < N < 60$, the suspension is referred to as *semiconcentrated,* with forced collisions between fibers
- For $N > 60$, the suspension is *concentrated* and has continuous fiber contact. Kerekes and Schell gave the following approximate equation for crowding factor:

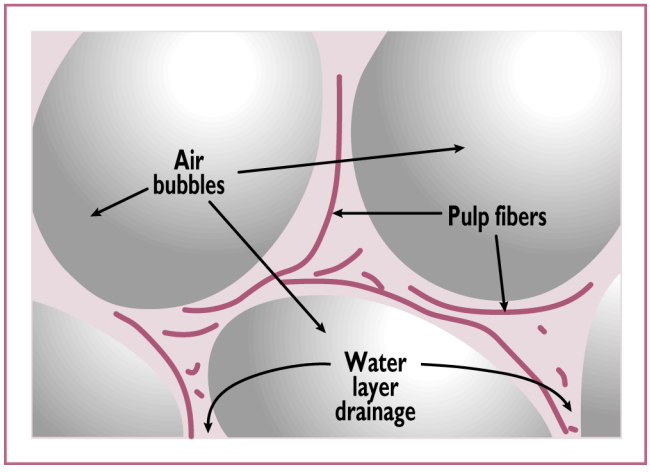
$$N \approx 5C_m L^2/\omega \qquad (1)$$

where C_m is the pulp consistency in percent, L is the length of the fibers in mm, and ω is the fiber coarseness in mg/m. The crowding factors were 21, 40, and 73 for the consistencies of 0.24%, 0.46%, and 0.83%, respectively. The highest pulp consistency used was therefore in the continuous contact regime, making it unlikely that the individual fibers would be entrained in the froth. It also is probable that because of increased floc strength, whole flocs were trapped in the froth so that there was very little fiber length differentiation between the pulp in the cell and the froth. The pulp slurries with consistencies of 0.24% and 0.46% were semiconcentrated, with forced collisions between fibers rather than continuous fiber-to-fiber contact, allowing individual fibers to be captured in the froth. Thus, fiber fractionation by flotation was possible at the two lower consistencies tested.

For two of the pine oil tests at C_m = 0.24%, the rate at which the mass of dry pulp was being recovered in the overflow is shown in **Fig. 8**. The



9. Cumulative recovery of fibers less than 1.5 mm and greater than 1.5 mm in length (C_m = 0.24% with pine oil)



10. Fibers in water layer of froth

rate was extremely high in the first minute of the test (over 20% of the total mass/minute) and then dropped to a much lower steady rate (2–5% of the total mass/minute). The rate of capture of pulp mass in the froth agreed with the visual observations of the amount of froth produced and pulp collected.

Recovery curves showing the kinetics of flotation are often used in the mineral processing industry for the scaleup of laboratory or pilot plant results to the mill size. To determine whether the flotation of fibers followed similar kinetics, a comparison of the recovery of the shorter fibers vs. the longer fibers in the froth was conducted. Analysis of the fiber distribution of the initial pulp and that of the fiber captured in the froth showed that 1.5 mm was the approximate length at which the pulp was fractionated (see Fig. 4). The cumulative recovery rate on a dry mass basis was calculated for tests 11 and 13, and the results are plotted in **Fig. 9**. The following kinetic relationship has been used to model the recovery curves [Kimpel and Hansen *(8)*] in the mineral processing industry:

$$R = a[1 - (1 - e^{-kt})/kt] \qquad (2)$$

where R is the mass recovery in percent, t is time in minutes, and a and k are parameters of the model. Parameter a gives the maximum recovery possible as time approaches infinity, while k is a measure of the recovery rate. A best fit of this model was calculated for both the long- and short-fiber fractions, and the resulting values of the parameters, where L indicates length, were as follows:

- For $L > 1.5$ mm, $a = 84.3$ and $k = 0.715$.
- For $L < 1.5$ mm, $a = 47.6$ and $k = 1.191$.

Comparing the values for a indicates that, over a long period of time, the mass recovery of fibers longer than 1.5 mm to the froth would be more than 80%, while the recovery of fibers shorter than 1.5 mm would be less than 50%. On that basis, significant differences between the froth and the pulp are attainable by flotation.

The question remains: What is the actual mechanism that causes preferential flotation of long fibers at low consistencies? In the mineral processing industry, froth flotation is used to float certain minerals, allowing the separation of valuable minerals from the less desirable or unwanted (gangue) minerals. This is normally accomplished by the addition of a reagent referred to as a *collector,* which alters the surface characteristics of selected mineral particles. If the desired mineral particles can be made more hydrophobic than the other minerals present, then they will have a greater tendency to attach themselves to an air bubble and will have a higher concentration in the froth. However, the separation of the desired mineral from the gangue is not only due to attachment to the bubbles. As the air bubbles rise through a slurry, they tend to entrain both the valuable minerals and gangue in the froth. As the froth layer builds in thickness, much of the entrained liquid drains back through the froth, carrying the unattached gangue particles with it [Jameson *(9)*].

Ajersch and Pelton *(10)* found that entrapment of longer wood fibers in a froth was the primary mechanism of separation, rather than surface activity of the fibers. They also discussed the influence of bubble size on the capture of fibers in froth. Our preliminary tests of wood pulp flotation in a column (results are not presented here) show that if the froth was removed as soon as it was formed, then the fiber length distribution in the captured froth was similar to the feed pulp. However, if the froth layer was allowed to build and drain before removal, then the fiber length distribution was significantly different than that of the feed pulp. It appears that the fine air bubbles rising through a pulp slurry entrain fibers so that the froth that is

KEYWORDS
Consistency, fiber length, fiber length distribution, flotation, foam, fractionation, softwood pulps, thermomechanical pulps.

formed has fibers contained in it. As the water film between the bubbles drains and returns to the pulp slurry, it carries with it the fines and the shorter fibers. The longer fibers in the froth are unable to negotiate the tortuous path of the liquid and remain trapped by the bubbles (see **Fig. 10**). When the drained froth is scooped from the cell, it therefore carries with it a fiber distribution consisting of a much higher proportion of long fiber than the original pulp. Since we were able to fractionate fibers of the same pulp on the basis of length, it would appear that the physical length of the fibers, rather than surface activity, is the most important parameter in flotation.

The results obtained here are different from those obtained when using flotation to deink a pulp. In flotation deinking, it is highly desirable to minimize the fiber loss to the froth. The pulp consistency must be kept high enough that a network of relatively strong fiber flocs is formed. The rising bubbles capture the hydrophobic ink particles and channel through the fiber network to the free surface, entraining less wood fiber than achieved in this study.

CONCLUSIONS

The primary cause of fiber fractionation by flotation was the physical entrapment of the longer fibers, rather than differing surface activity of the fibers. The feed pulp consistency had a direct effect on the fractionation performance. The higher the pulp consistency, the greater is the number of fiber-to-fiber contacts, which increases the floc and network strength. At some value, the agitation in the cell could not break the fiber network, and the longer fibers were not floated. During flotation of wood fiber at lower consistencies (0.25–0.50%), the longer fibers were more likely to be captured in the froth.

Furthermore, the addition of a surfactant to promote the creation of froth was beneficial. The flotation results for 100% softwood TMP when pine oil was added were considerably better than those with no additive. For the tested pulp consistency of 0.24% with pine oil, the flotation process provided excellent fractionation. In fact, the recovery curves for the long and short fibers show that nearly the maximum amount of fiber longer than 1.5 mm was recovered in the froth in the 12-min test runs.

RECOMMENDED FUTURE WORK

The semibatch process used has produced very encouraging results; however, a number of areas need to be investigated. Laboratory tests of a continuous flotation system should be conducted. A survey of possible surfactants and their optimum concentrations needs to be done. The feed pulp consistency that gives the most efficient flotation of longer fibers needs to be determined. Finally, the relationship between froth bubble size and the length of fibers captured needs to be defined. **TJ**

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