

Fractionation of wood pulps by continuous flotation

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

MECCHANICAL WOOD PULPS AND pulps derived from recycled paper exhibit wide fiber length distributions. Fiber fractionation of these pulps into fractions based on fiber length offers a number of advantages. A pulp's properties may be tailored toward its end use by blending appropriate amounts of different-length fractions (1). The strength of the pulp may also be improved by separate treatment regimes for the individual-length fractions and the subsequent reblending into a whole pulp (2). Various grades of pulp may be fractionated from recycled pulp, increasing its economic value (3). However, to realize these advantages, an inexpensive technique for fiber fractionation is required. This work investigates the use of a continuous flotation process to fractionate mechanical pulp into streams of different lengths.

In 1997, Eckert *et al.* (4) fractionated softwood thermomechanical pulp (TMP) using a semibatch flotation process. The results given in that paper agreed with the conclusions of Ajersch and Pelton (5): entrainment and then entrapment of longer fibers in the froth was the primary mechanism of separation. This led us to believe that the length of the fibers trapped in the froth should be related to the size of the bubbles generated in the cell. The present study, therefore, had two objectives. The first was to show that a continuous flotation process could successfully fractionate mechanical softwood pulps. The second focused on

studying the correlation between bubble size and length of fiber captured in the froth.

A laboratory flotation cell was modified to allow continuous feed, froth, and tailing streams. The parameters that we varied were feed flow rate, impeller rotation speed, air flow rate, surfactant concentration, and feed consistency. For each test run, the froth stream was captured over 2-min time intervals and analyzed for length distribution and pulp consistency. Furthermore, a bulk sample of the tailings stream was analyzed, and a videotape of the cell was taken to determine bubble sizes. We found that mean bubble size correlated directly to the average length of the fiber captured in the froth. Also, the concentration of surfactant added to the feed stream had the greatest effect on bubble size, while the impeller speed had the least.

EXPERIMENTAL METHOD

A modified Wemco laboratory flotation cell was used in this experiment, as shown in **Fig. 1**. The setup allowed the feed flow rate, air flow rate, and impeller speed to be easily controlled and measured. The feed flow rate and impeller speed were controlled using variable-speed drives on the feed pump and impeller motors. The level of the pulp in the cell was controlled with a variable-height overflow with siphon breaker in the tailings line. The air flow rate was measured and controlled using a rotameter. The feed flow rate was measured with a magnetic flowme-

ABSTRACT

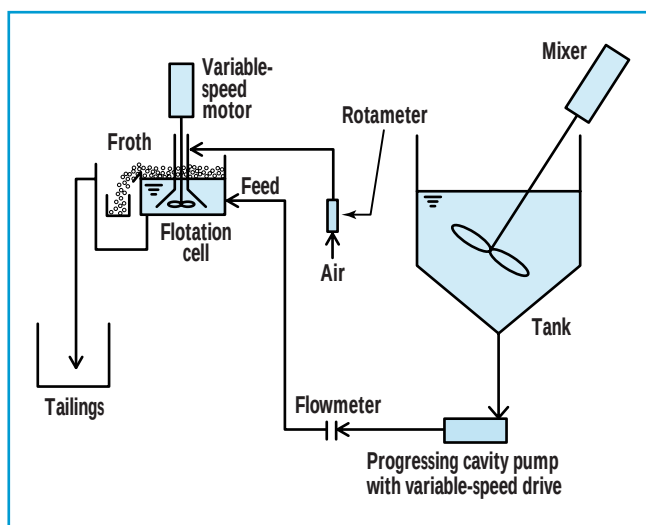
Fractionation of 100%-softwood TMP has been successfully demonstrated using a continuous flotation process. A correlation between the mean bubble diameter and the length of fiber captured in the froth has been shown. The relative effects of feed flow rate, air flow rate, surfactant concentration, impeller speed, and pulp consistency on the size of bubbles generated are shown. We found that the mean bubble diameter correlated directly to the average length of the fiber captured in the froth. The surfactant concentration that was added to the feed stream had the greatest effect on the bubble size, while the impeller speed and air flow rate had the least. The results presented give valuable insights into both fiber fractionation and fiber loss from flotation deinking processes.

Application:

This continuous flotation process may be used to recover valuable long fibers from mechanical or recycled pulps.

ter, while the impeller speed was measured using a mechanical tachometer attached to the drive-shaft.

The softwood pulp was prepared in 150–200-L batches in a large tank, and approximately 40 L were transferred to the feed tank for each test. Surfactant (pine oil) was added, and then the pulp was allowed to mix for 1–2 hours before the experiment was run. For the initial fill, about 4.5 L of pulp was pumped from the feed tank into the 5.5-L flotation cell. A sample of the feed in the cell was taken, and then the air was turned on to the desired flow rate. The impeller motor was turned on and set to the appropriate rotation speed. A timer was started when the froth first flowed over the lip of the cell. The froth was collected in 2-min intervals



1. Schematic of experimental equipment.

over a 20-min time span. At the end of a test, a tailings sample was dipped from the tailings container. The volume of each of the froth samples and that of the total tailings were measured and recorded. A small portion of each sample was analyzed in the Optest Fiber Quality Analyzer to determine the average fiber lengths and distributions. The remainder of each sample was filtered through tared papers, dried, and weighed to determine consistency.

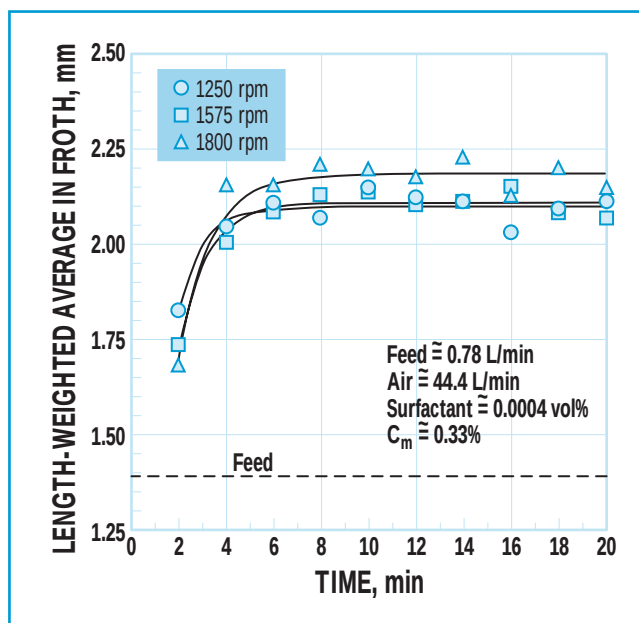
To facilitate bubble size measurements, the pulp in the cell was videotaped through the cell wall, at a level just below the froth. The video camera was set to macro focus and had a shutter speed of 1/4000 second. Approximately 1 min of tape was shot for each test at a time of 10–12 min after the start of the test. Individual frames of the tape were then captured on a personal computer equipped with a frame grabber and were printed. The bubbles in each of the pictures were counted and sized using an optical analyzer (Buehler Omnimet Image Analyzer). A clear millimeter scale was attached to the wall of the flotation cell, allowing the scale to be seen in every frame of the tape.

RESULTS AND DISCUSSION

The following parameters were changed: impeller rotation speed, surfactant concentration, feed consistency, feed flow, and air flow rates. The influence of each of these on the fiber recovery is discussed as follows.

The effect of impeller rotation speed

The continuous flotation process was tested at impeller speeds of 1250, 1575, and 1800 rpm. Figure 2 shows the length-weighted average of the fiber length captured in the froth over the test period. The 100%-softwood TMP feed had a length-weighted fiber length of 1.39 mm and a consistency of 0.33%. For each of the speeds, the figure shows that the average length of fiber captured in the froth reached a steady-state value over the test. A steady



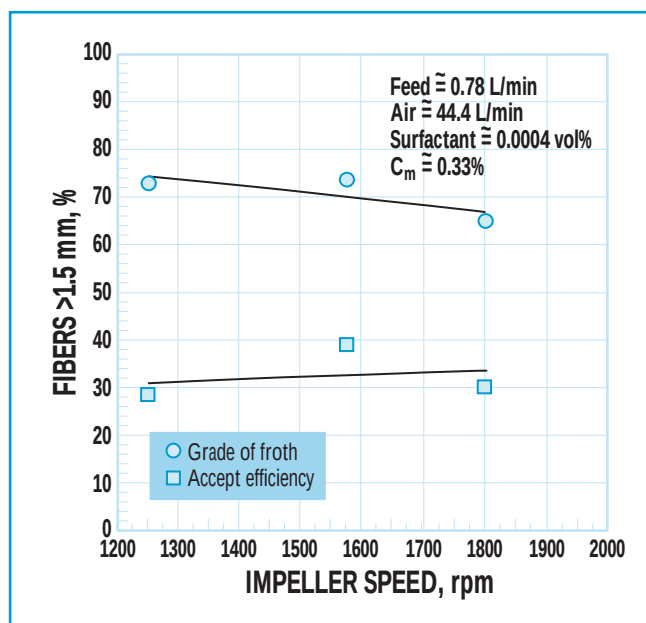
2. Effect of impeller rotation speed on length of froth captured.

state was attained within 6–8 min after starting an individual test. The open symbols represent the measured values, while the lines are a curve fit of the following equation to those values:

$$L = a(1 - e^{-bt}) \quad (1)$$

The parameter a in Eq. 1 gives an average value for the length of fiber captured during the steady-state portion of the test. For the rotation speeds of 1250, 1575, and 1800 rpm, the average length of fiber captured in the froth was 2.10, 2.11, and 2.18 mm, respectively. Therefore, the average length of the fraction of fiber captured in the froth was not significantly influenced by the impeller speed.

Figure 3 shows the accept efficiency and grade of the fibers in the froth. The *accept efficiency* is defined as the ratio of the mass of fibers in the froth longer than 1.5 mm to the mass of the fibers longer than 1.5 mm in the feed for an equivalent time period. It is a measure of the recovery of long fibers in the froth. The *grade* is defined as the mass of the fibers that is longer than 1.5 mm to the total mass of fibers in the froth. The grade is a measure of the length distribution of the fibers in the froth. The average grade of the feed stream is approximately 40% long fibers (>1.5 mm). For the impeller speed of 1575 rpm, the accept efficiency of long fibers was almost 40%, while the accept efficiency was approximately 30% for both of the other speeds. For an increasing speed, the accept efficiency of long fibers showed a very slight increase, while the grade of the froth decreased slightly. This indicated that a higher impeller speed not only enhanced recovery of long fiber but short fiber as well. However, as is shown in Fig. 3, the effect of impeller speed was very small. For all the tests,



3. Effect of impeller rotation speed on grade and accept efficiency of fibers captured.

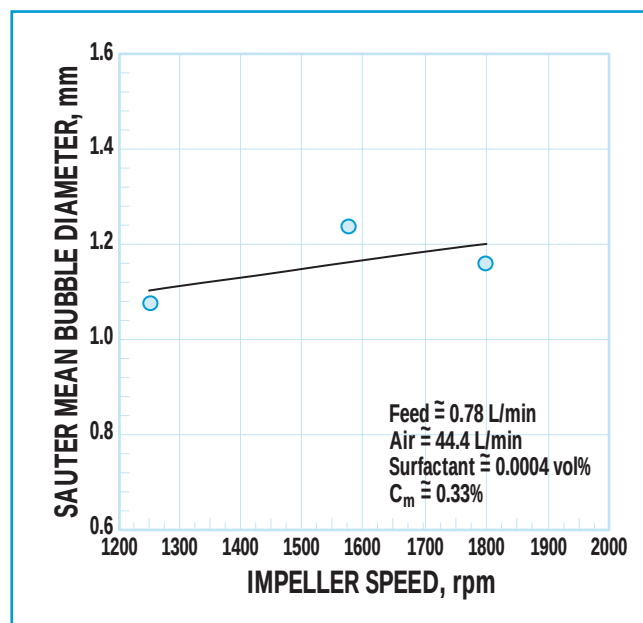
the accept efficiency and grade were the average of the samples taken during the steady-state portion of the run (6–18-min samples).

Figure 4 shows the Sauter mean diameter of the air bubbles generated in the cell as a function of the impeller speed. Again, at the impeller speed of 1575 rpm, the bubble diameter was the largest; however, over the speed range, the diameters did not vary widely.

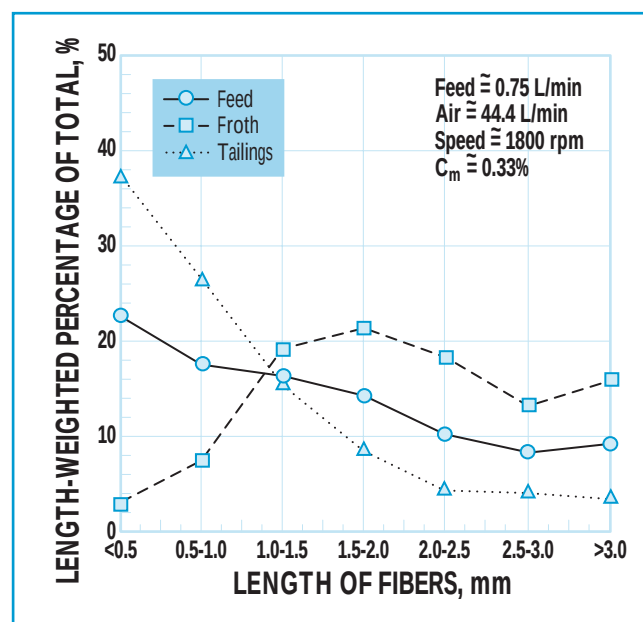
Figure 5 shows a typical comparison of the length-weighted fiber distributions for the feed, froth, and tailings for the 1800-rpm test. The froth contained a larger proportion of fiber longer than 1.5 mm than was in the feed. As well, the tailings contained a smaller proportion of fiber longer than 1.5 mm than was in the feed. Therefore, the froth removed a significant proportion of long fibers from the feed, leaving tailings with a shorter fiber length distribution.

The effect of surfactant in the feed stream

Since the dry fiber contained some natural surfactants that leached into the fluid as the pulp was reslushed, the exact concentration of surfactant in the feed stream to the cell was not known. The amount of added surfactant (pine oil) was measured, and hence the concentration of surfactant added to the feed was calculated. In the present study, the *surfactant concentration* was defined as the concentration of added surfactant, rather than total surfactant. We had hoped to use surface tension of the supernatant to characterize the amount of surfactant present; however, a series of tests showed that the surface tension did not correlate well with the bubble sizes. Also, samples of pulps prepared under similar conditions had wide differences in surface tension but not in fractionation performance. As a result, the use of surface tension as a measure of surfactant present was abandoned.

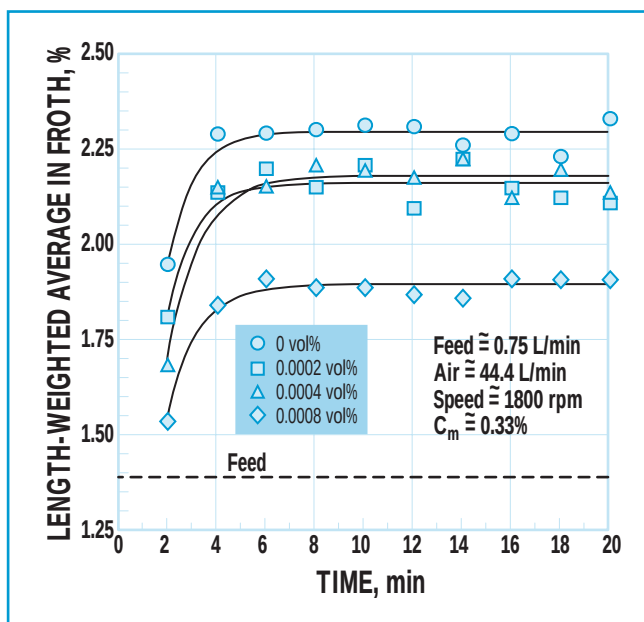


4. Effect of impeller rotation speed on Sauter mean bubble diameter.

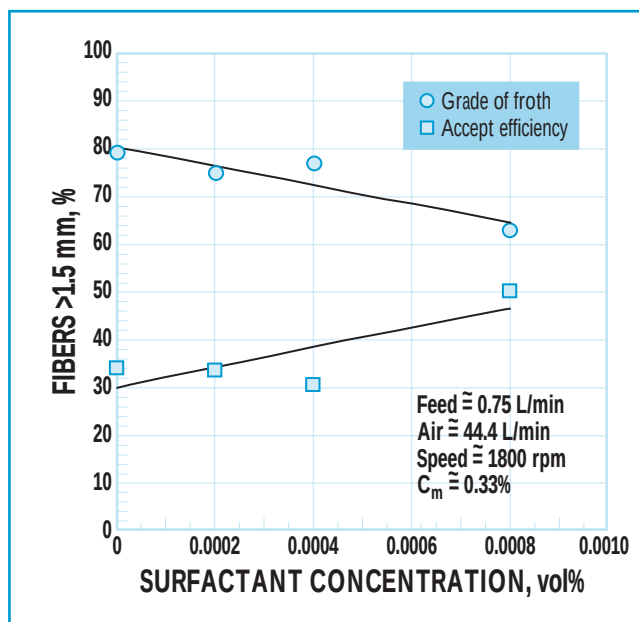


5. Comparison of fiber length distributions in feed, froth, and tailings.

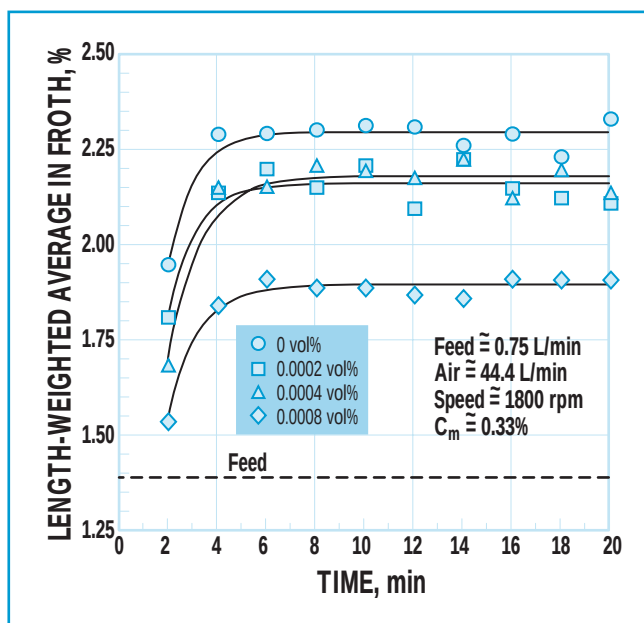
In this study, added surfactant concentrations of 0, 0.0002, 0.0004, and 0.0008 vol. % were used. For each of the tests, the feed consistency was 0.33%, the impeller rotation speed was 1800 rpm, and the air flow rate was 44.4 L/min. **Figure 6** shows the variation of the average fiber length captured in the froth with the surfactant concentration. As the concentration of surfactant was increased, the steady-state length of fiber captured in the froth decreased. With no added surfactant, we were able to capture a fraction with very high average lengths (2.29 mm). However, the amount of natural surfactant present



6. Effect of added surfactant on length of fiber captured.



7. Effect of added surfactant on grade and accept efficiency of fiber captured.



8. Effect of added surfactant on Sauter mean bubble diameter.

depends on the particular pulp used—and therefore on the species and process conditions used in its manufacture. Very little difference was observed between the surfactant concentrations of 0.0002 and 0.0004 vol. %, which resulted in average fiber lengths of 2.16 and 2.18 mm, respectively. When the surfactant concentration was 0.0008 vol. %, the shortest average fiber length was captured (1.90 mm).

Figure 7 shows the effect of surfactant concentration on fiber accept efficiency and grades. The accept efficiency increased steadily with increased surfactant concentration; however, the grade of the froth also decreased steadily. This would indicate that the amount of long fiber

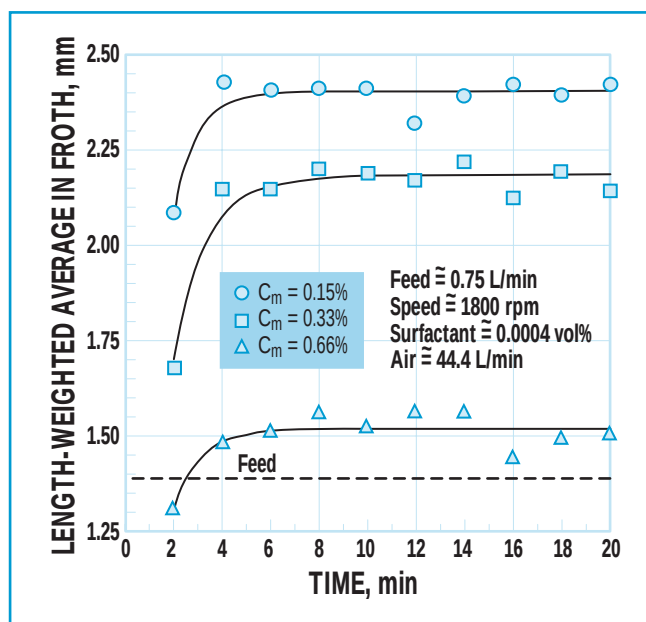
captured increased with an increase in surfactant and that the amount of short fibers increased as well. By visual observation, the rate of froth production was greatly increased at the highest surfactant concentration, which would tend to increase the amount of fiber captured in the froth.

Figure 8 shows the variation in the bubble size generated as the concentration of added surfactant was changed. This graph correlates well with Fig. 7, since the bubble size decreased significantly with increasing surfactant concentration. The smaller bubbles reduced the grade of the froth by capturing shorter fibers as well as long ones. This also increased the accept efficiency by capturing a larger portion of all the fiber.

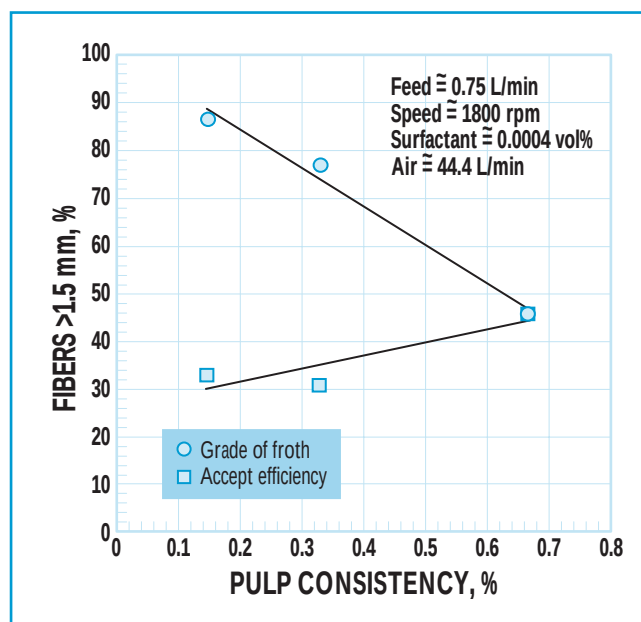
The effect of feed consistency

The consistency of the feed stream was also varied from 0.15% to 0.66%. For these tests, the feed rate was approximately 0.75 L/min, the air flow rate was 44.4 L/min, the impeller speed was 1800 rpm, and the concentration of added surfactant was 0.0004 vol. %. Figure 9 gives the variation in fiber length captured by the froth with differing pulp feed consistencies. The lowest consistency (0.15%) gave the highest average length captured (2.40 mm). The pulp consistency of 0.33% gave an average fiber fraction of 2.18 mm, while the highest consistency of 0.66% gave an average fiber fraction of 1.53 mm. The feed had a length-weighted average of 1.39 mm, so the high-consistency feed of 0.66% gave a fraction that was not significantly longer than feed.

Figure 10 shows the variation in accept efficiency and grade for different feed consistencies. As the consistency was increased, the recovery of long fibers to the froth increased significantly. However, the grade of the froth decreased dramatically.



9. Effect of feed consistency on length of fiber captured.

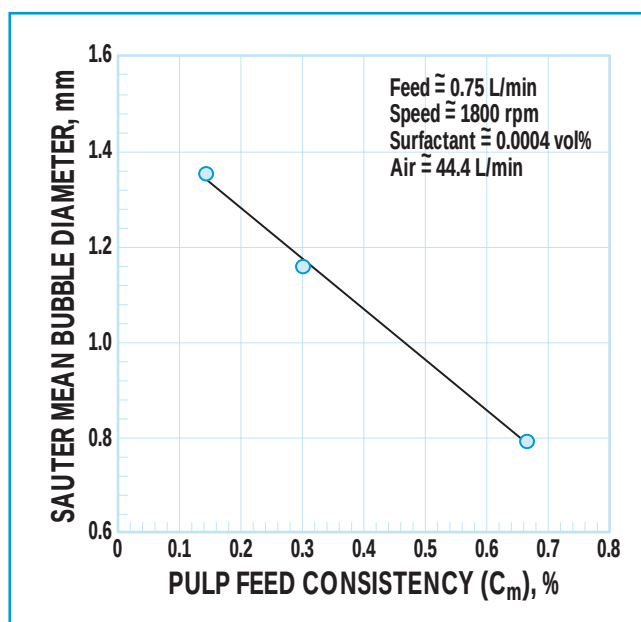


10. Effect of feed consistency on grade and accept efficiency of fiber captured.

Figure 11 shows the variation in bubble size with consistency. The Sauter mean diameter of the bubbles decreased significantly with pulp feed consistency as well. This correlates well with the drop in the grade of froth but an increase in accept efficiency. Decreasing bubble size indicates that the surfactant concentration increased with pulp consistency. However, since the concentration of added surfactant was 0.0004 vol. % for all three tests, the increase in surfactant must be due to natural surfactants coming from the wood fiber during reslushing.

The change in fractionation performance with pulp consistency can be attributed to two factors. As previously explained, the higher pulp consistency results in a higher level of naturally occurring surfactants, which decreases bubble size and fractionation performance. Also, the higher consistency results in a higher crowding factor, as defined by Kerekes and Schell (6). For the pulp consistencies of 0.15, 0.33, and 0.66%, the corresponding crowding factors are 13, 29, and 58, respectively. The two lowest consistencies were therefore in the semiconcentrated regime with forced collisions between fibers. The highest consistency used was on the border between the semiconcentrated and concentrated regimes.

The fractionation performance would indicate that the pulp was in the concentrated regime with continuous fiber contact. That means the pulp had formed a mesh with a large enough strength that the most of the fibers were not free to float with the froth. This was also confirmed by the consistencies of the froth. For the two lowest feed consistencies, the froth consistency produced was higher than that of the feed. For example, for the feed consistencies of 0.15 and 0.33%, the froth consistencies were approximately 0.29 and 0.52%, respec-

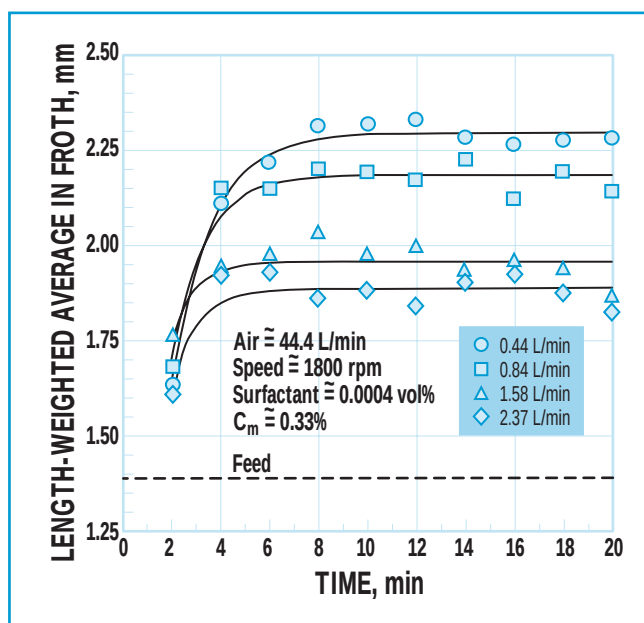


11. Effect of feed consistency on Sauter mean bubble diameter

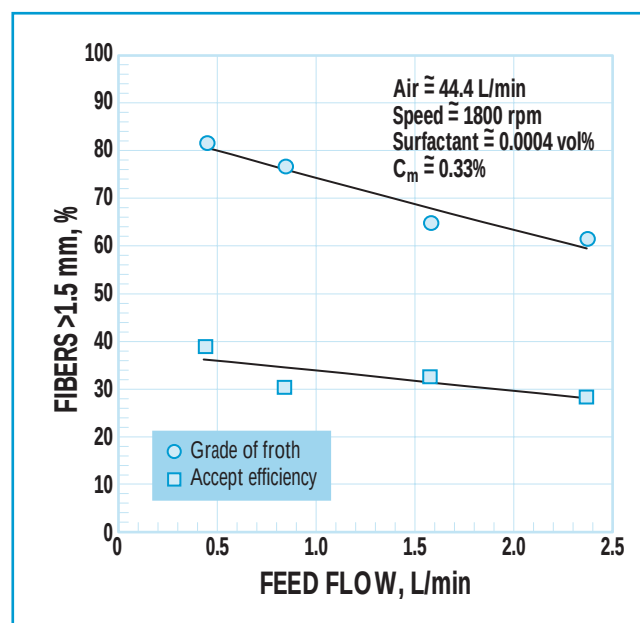
tively. However, at the high consistency, with the pulp being in the concentrated regime, the average consistency of the froth was 0.48% compared to the feed consistency of 0.66%. Thus relative to the feed, more water than fiber was being transported into the froth.

The effect of feed flow rate

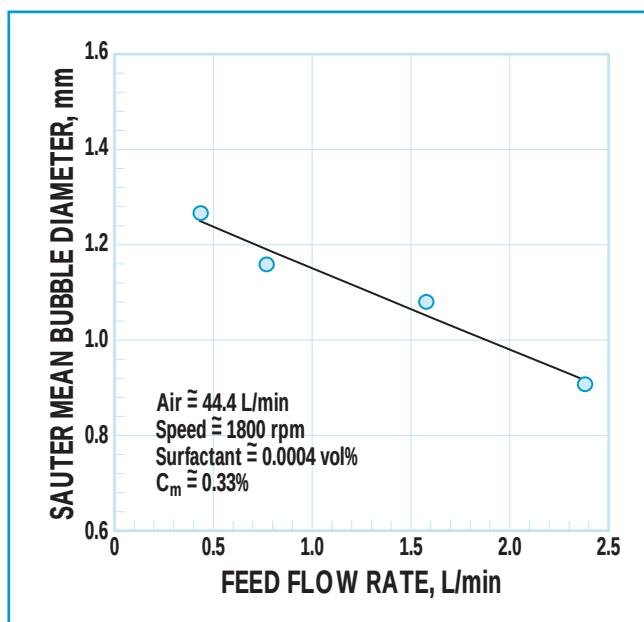
The effect of feed flow rate was determined by testing four different feed flow rates in the cell. The rates were 0.44, 0.84, 1.58, and 2.37 L/min. For all of these tests, the feed consistency was 0.33%, the air flow rate was 44.4 L/min, the added surfactant concentration was 0.0004 vol. %, and the impeller rotation speed was 1800 rpm.



12. Effect of feed flow rate on length of fiber captured



13. Effect of feed flow rate on grade and accept efficiency of fiber captured



14. Effect of feed flow rate on Sauter mean bubble diameter

Feed flow rate, L/min	Average fiber length captured, mm	Mean residence time, min
0.44	2.29	10.3
0.84	2.18	5.4
1.58	1.95	2.8
2.37	1.88	1.9

I. Average length of fiber and mean residence time vs. feed flow

Air flow rate, L/min	Accept efficiency in froth of long fibers, %	Grade of froth, % of long fibers	Mean bubble size, mm
25.4	48	67	1.03
44.4	30	77	1.16

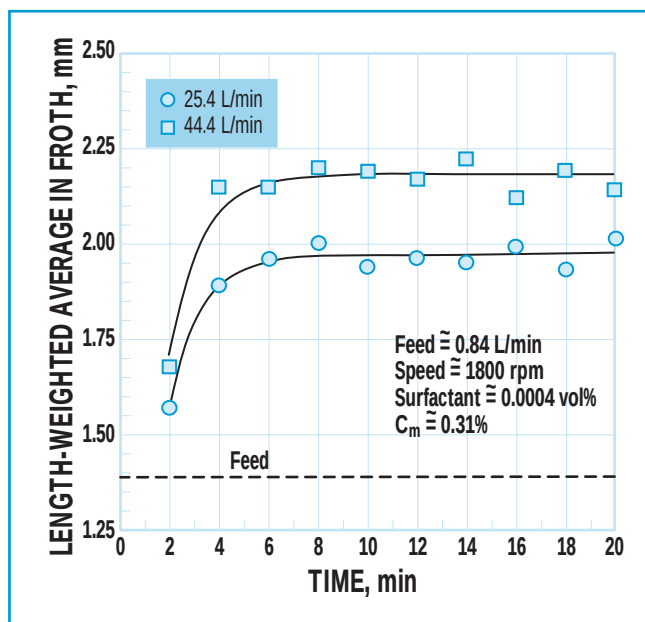
II. Accept efficiency, grade, and mean bubble size vs. air flow rate

Figure 12 shows the variation in fiber length with feed rate. As shown in this figure and in Table I, the length of fiber captured in the froth decreased with an increased feed flow rate.

Figure 13 shows the variation in accept efficiency of the long fiber and the grade of the froth captured. Both the accept efficiency and grade decreased with increasing flow rate. It would be natural to expect a decrease in accept efficiency with increased flow rate, due to the reduced mean residence time. There was approximately a factor-of-five decrease in residence time from the lowest to highest feed flow rate. Also, during the run, a higher feed flow rate would quickly replenish the sur-

factant that was being lost to the froth; therefore, one would expect a higher surfactant concentration in the bulk of the flotation cell at steady state. The decreased grade of the froth was therefore attributed to smaller bubbles being generated.

The variation of bubble size with the feed flow rate is shown in Fig. 14. Again, the bubble size shows an approximately linear relationship with the feed flow rate over the range tested. As previously indicated, the bubble size does decrease significantly with increased feed rates, confirming the hypothesis that the steady-state surfactant concentration in the cell is higher with higher feed flow rates.



15. Effect of air flow rate on length of fiber captured

The effect of air flow rate

Two air flow rates, 28.4 and 44.4 L/min, were tested with this flotation cell. These were the upper and lower limits of airflow that could be achieved with the equipment used. For these two tests, the pulp consistency averaged 0.31%, the feed flow rate was 0.84 L/min, the surfactant concentration was 0.0004 vol. %, and the impeller speed was 1800 rpm.

Figure 15 shows the variation in fibers captured in the froth vs. air flow rate. At steady state with a lower airflow, the captured fibers were approximately 1.97 mm, while at the higher air flow rate, the captured fibers were approximately 2.18 mm in length.

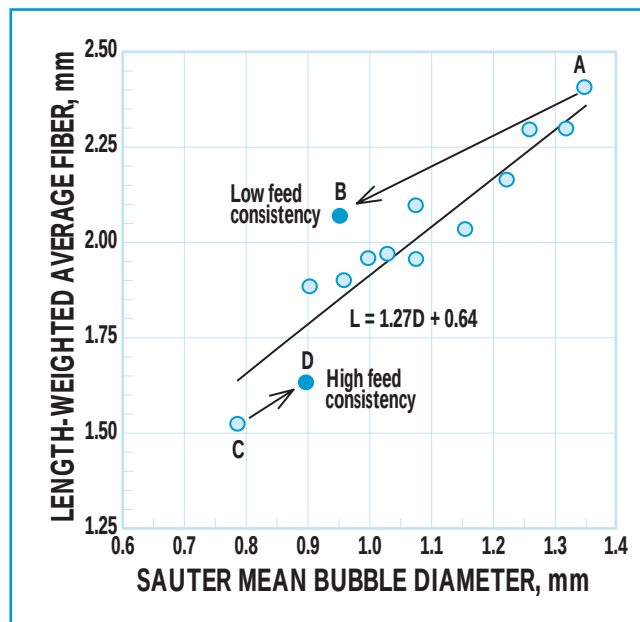
Table II shows the change in accept efficiency, grade, and mean bubble size with air flow rate. The accept efficiency of long fibers reduced from 48% to 30%, while the grade of the froth increased from 67% to 77% when the air flow rate was increased from 28.4 to 44.4 L/min. The Sauter mean diameter of the bubbles was 1.03 mm at the low air flow rate and 1.16 mm at the high air flow rate. Again, the larger air bubble size correlates well with a decrease in recovery of longer fibers but an increase in the grade of the froth.

The effect of bubble size

In all of the tests previously discussed, the various manipulated parameters had an effect on the length of the fibers captured in the froth. The mean bubble diameter was affected by the manipulated parameters as well. This strongly suggested that there was a correlation between bubble size and length of fiber captured.

To check this hypothesis, the Sauter mean diameters of the bubbles in each test were plotted against the average fiber length captured in the froth at steady state (Fig. 16). As shown in this figure, over the range of bubbles generated, the average fiber length had a nearly linear relationship. This is strong evidence that the entrainment and entrapment of the fibers by the bubbles are the primary mechanisms of fractionation, as discussed in Ajersch and Pelton (5) and Eckert *et al.* (4).

Figure 16 also shows the effect of surfactant concentration on the relationship between Sauter mean bubble diameter and average fiber length. To demonstrate this relationship, two additional tests were conducted that repeated the upper and lower points on Fig. 16 but had different surfactant concentrations. The



16. Length of fiber captured as influenced by the bubble size for all runs

test that generated the largest bubble diameter and fiber length was run at an impeller speed of 1800 rpm, a feed rate of 0.75 L/min, an air flow rate of 44.4 L/min, and a surfactant concentration of 0.0004 vol. % with a feed consistency of 0.15% denoted by A in Fig. 16. This test was repeated with an increased surfactant concentration of 0.0008 vol. %.

We found that both the mean bubble diameter and average fiber length captured in the froth were reduced, as shown by the solid circle B in Fig. 16. The test that gave the smallest bubble diameter and fiber length captured was run at an impeller speed of 1800 rpm, a feed flow rate of 0.75 L/min, an air flow rate of 44.4 L/min, and a surfactant concentration of 0.0004 vol. % with a feed consistency of 0.66%, as shown by circle C in Fig. 16. The repeated test had no added surfactant. The Sauter mean bubble diameter and average fiber length captured were both increased. This is also shown as a solid circle D in Fig. 16.

A comparison of these two additional tests has shown that even with the highest and lowest feed consistencies, similar mean bubble diameters could be obtained by merely varying the surfactant con-

centration. However, there was a difference in the length of the fiber captured for these two tests. This was due to the strength of the fiber network, which is dependent on feed consistency. This confirmed that the bubble size was most strongly influenced by the amount of surfactant present, rather than the fiber-bubble interaction. The amount of surfactant present in the cell depended on the pulp feed consistency, the amount of surfactant added, and the feed flow rate.

Scaleup

The experimental setup of the present study was scaled down from a Wemco Model 120 industrial flotation cell having a volume of 8.43 m³, characteristic length of 3.05 m, impeller diameter of 0.56 m, and aspect ratio of 5.45. The laboratory cell had a volume of 0.007 m³, characteristic length of 0.277 m, and impeller diameter of 0.0508 m. Note that we had reduced the scaled-down liquid height so that the volume was 4.5 L rather than 7 L.

The impeller speed can be scaled up from a laboratory cell to an industrial cell by the equation $K=S/D^{0.33}$, where S is the impeller tip speed and D is the impeller diameter. For a constant K , 1800 rpm in the laboratory cell is equivalent to 360 rpm in the Wemco Model 120 industrial cell. Similarly, the air flow rate can be scaled by the equation $N_q=Q/(ND^3)$, where Q is the air flow rate, N is the impeller speed, and D is the impeller diameter. For 1800 rpm, the laboratory air flow rate of 44.4 L/min scales to approximately 100 L/min in the industrial cell. The feed rate can be scaled up based on a similar residence time. The laboratory cell had a feed rate of 0.75 L/min and a residence time of 6 min. This is equivalent to approximately 1400 L/min for the industrial flotation cell. From these parameters, it would appear possible to scale up the laboratory cell to an industrial size flotation cell.

There are disadvantages to using this method for fiber fractionation. The first is a long residence time, which would require large cell volumes with low feed rates. The second is that an industrial fractionation process would probably require multiple stages of cells to maximize recovery of long fiber. The third is that this process would require large amounts of water due to the need for low feed consistency. The proof of practicality for fiber fractionation requires testing on an industrial scale.

CONCLUSIONS

This study has shown that there is a strong correlation between the mean bubble diameter and the average length of fiber captured in the froth. The larger the mean bubble diameter, the longer the average length of fibers that were captured. The bubble size was most dependent on the amount of surfactant added. Pulp consistency also had a strong effect on the accept efficiency of the fibers. This was due to the naturally occurring surfactant and the intimacy of fiber contact. Impeller speed and air flow rate had a very small effect on the capture of long fibers. TJ

Eckert is a project and research engineer at Beta Machinery Analysis Ltd. 300, 1615 10th Ave. SW, Calgary, AB T3C 0J7, Canada. Afacan is a faculty service officer and Masliyah is a professor at the University of Alberta, Department of Chemical and Materials Engineering, Edmonton, AB T6G 2G6, Canada.

The financial support of the Natural Sciences and Engineering Research Council of Canada and Paprican through the Networks of Centres of Excellence: Mechanical Pulping Network is gratefully acknowledged.

Received for review March 17, 1998.

Revised Oct. 22, 1998.

Accepted Dec. 5, 1998.

LITERATURE CITED

1. Moller, K., de Ruvo, A., Norman, B., et al., *Pap. Technol. Ind.* 20(3): 110(1979).
2. Behera, N. C. and Basu, S., *Appita J.* 34(6): 485(1981).
3. Abubakr, S. M., Scott, G. M., and Klungness, J. H., *Tappi J.* 78(5): 123(1995).
4. Eckert, W. F., Masliyah, J. H., and Afacan, A., *TAPPI J.* 80(5): 210(1997).
5. Ajersch, M. and Pelton, R., *Proceedings of the 3rd Research Forum on Recycling*, CPPA, Montreal, 1995, p. 27.
6. Kerekes, R. J. and Schell, C. J., *J. Pulp Paper Sci.* 18(1): 138(1992).