Drainage and Fractionation of Wood Fibers in a Flotation Froth

J.Y. Zhu and Freya Tan

ABSTRACT

Understanding fiber fractionation in a froth is very important to the quality of recovered fibers in flotation deinking operations. Fiber length is a very important fiber quality parameter in paper-making. For example, long fibers tend to produce a paper with higher tear strength than short fibers. In this study, fibers in froth collected at different froth drainage times and from different heights were analyzed to obtain fiber length distributions. The length distribution of fibers in the collected froth showed a lower fraction of short fibers (<0.8 mm) and a higher fraction of long fibers (> 0.8 mm) than those in the original pulp sample. The length-weighted mean fiber length in the collected froth was 11% longer than the original TMP tested. A fiber length fractionation phenomenon was also observed along the froth vertical direction, that is, fiber collected from the upper part of a froth has a relatively lower fraction of short fibers and a longer mean fiber length than those collected in the bottom part of the froth or the original pulp. The fiber fractionation phenomenon revealed in this study indicated that flotation deinking selectively rejects more fibers greater than **2** mm compared with the original pulp sample, thus significantly impacting the quality of recovered fibers.

KEYWORDS

Deinking, Drainage, Fiber fractionation, Fiber length, Fiber yield, Flotation, Foam, Froth, Paper recycling

INTRODUCTION

It is well known in flotation deinking that fiber entrainment [1-3] into froth by water carry over is the main mechanism of fiber yield loss in industrial flotation deinking operations. Furthermore, the fibers rejected in froth are different from those in the suspension in terms of primary fiber length, or morphology. For example, foam fraction is rich in long fibers. while short fibers remain in the pulp suspension, as found by Li and Muvundamina [4]. The fines content in the reject stream can be either lower or higher than that in the feed stock depending on bubble size and fiber consistency in feed stock according to Ajersch and Pelton [2]. The dissimilarity of fiber properties between those in the reject stream and feed stock is called fiber fractionation. Understanding fiber fractionation has industrial significance because fractionation affects the quality of the fibers recovered. For example, fiber length is a very important fiber quality parameter, i.e., long fibers tend to produce paper with high tear strength. Fiber fractionation is caused by the dissimilarities in fiber flocculation, entrainment, or drainage among fibers of different length or morphology near the suspension and froth interface and within the froth once the fibers are entrained. Without experimental data, Ajersch and Pelton [2] qualitatively explained how fiber flocculation through entrainment and drainage may affect fiber fractionation. One objective of the present study is to demonstrate that time-dependent characterization of fiber fractionation in the laboratory can be an effective tool to understand key factors controlling fiber fractionation, so that knowledge to achieve favorable fiber fraction in industrial flotation deinking operations can be obtained.

Water drainage in aqueous froth has been well understood, which lays the foundation for the understanding of fiber movement or drainage in flotation froth. It is understood that the density difference between the gas and water in the froth causes the gas to rise and water to flow down under gravity. Process water drainage in aqueous froth is understood to happen in the following way. Water is drained mainly through the plateau border (PB) channels where neighboring liquid films form between the faces of the polyhedral bubbles. A one-dimensional unsteady continuity equation can be applied to describe the Poiseuille water flow in PB channels [5-9]. Water drainage also causes the destruction of the froth and can be modeled using the

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unsteady material balance of gas in the froth [10- 11]. Draining of fibers in flotation deinking froth has been hypothesized by Robertson and others [12] and Zhu and others [13]. These researchers found that water and surfactant spray applied to the top of froth resulted in a decrease of fiber rejection loss in their flotation deinking experiments, respectively. They explained that the decrease may. be partially caused by the effect of liquid spray washing (fiber draining by water carryover). Recently, we conducted time-dependent fiber suspension flotation froth drainage study and found that the water drainage in froth caused an increase in fiber consistency in the collected wet froth reject stream [14]. We also demonstrated that fiber drainage occurred in flotation froth but at a slower speed [14, 15] than that of water in the same froth. Furthermore, fiber drainage is mainly caused by water carryover in PB channels [15]. This finding on fiber drainage in flotation froth provides opportunities for developing technologies to improve fiber yield in flotation deinking operations. The study also provides the scientific base for the study of effect of fiber drainage on fiber fractionation through flotation as hypothesized by Ajersch and Pelton [2].

The subject of pulp entrainment into froth has been extensively studied in mineral flotation [16-18]. However unlike mineral particle suspension, wood fibers are not uniformly dispersed in water and are easily flocculated to form fiber network or flocs [19-21] under consistencies seen in industrial flotation deinking conditions. The study on the effect of fiber flocculation and entrainment on fiber fractionation in flotation is very limited. Ajersch and Pelton [2] provided a glimpse of how fiber consistency (a key parameter affecting fiber flocculation [21]) and bubble size (a parameter controlling the diameter of PB channels [9] into which fiber or fiber flocs entrained) affecting final fiber content in froth without accounting for the effect of froth drainage on fiber fractionation. This study is the first step toward developing a comprehensive understanding of fiber fractionation in industrial flotation deinking operations through examining the effects of entrainment and drainage in fiber fractionation in laboratory flotation experiments.

EXPERIMENTAL

Flotation Cells

A column flotation cell as shown schematically in Figure 1 was made in-house using an acrylic tube with an inner diameter of 15.9 cm. The height of the flotation cell was 108 cm. The aeration medium was a circular acrylic plate of 6.4 mm thickness with 16 drilled holes of 0.3 mm diameter, uniformly distributed to produce a froth equivalent to those seen in flotation deinking operations. To ease froth collection, a stainless steel collar with a platform was mounted at the top of the flotation column. Half the surface

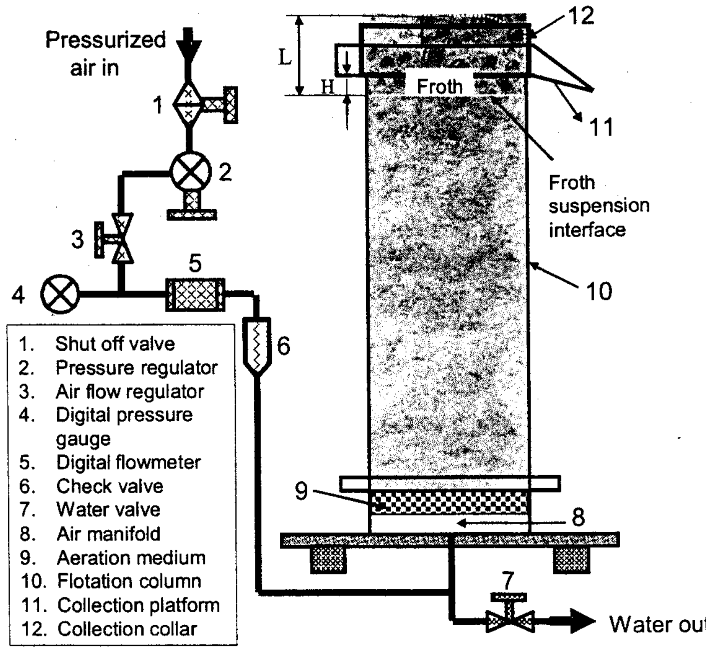

Figure 1. **A schematic diagram of the column flotation cell.**

of the platform was leveled with the top end of the flotation cell, and the other half was an inclined channel so that liquid or froth could easily flow out of the column for collection. In-house pressurized air was used for flotation. A pressure regulator and a flowmeter (model FMA-A2317, OMEGA, Stamford, Connecticut) were used to regulate the air flow rate into the column. A pressure of about 6.2 kPa was set during flotation. A check valve was also installed in the air flow line to prevent water back flow to the air flow meter.

Fibers

A mechanical pulping process was employed to produce wood fibers (thermomechanical pulp (TMP)) primary from lodge pole pine (47%), Douglas-fir (42%), and some western hemlock (8%) in a commercial pilot plant disk refiner (Andntz, Springfield, Ohio). An unrefined bleached softwood kraft pulp sample was obtained commercially. The Canadian Standard freeness of the TMP and kraft pulp samples was 130 and 700 mL, respectively, measured by Technical Association of the Pulp and Paper Industry (TAPPI) standard method T 227 - om-94 [22]. The fiber lengths of the two pulp samples were analyzed by a Kajaani FS-100 fiber analyzer.

Chemicals

Flotation experiments were conducted using Triton X-100 (TX-100, a nonionic octyl phenyl oxyethylenic surfactant), analytical grade (J. T. Baker Inc., Phillipsburg, New Jersey) as surfactant to stabilize froth.

Froth Flotation

The fiber consistency in the suspension was 0.5% for all the flotation experiments conducted. The aeration flow rate was set at 20 standard liters per min. The height of the suspension level was varied to obtain spatial distribution of water and fiber in froth. A cylindrical collar with a height of 13 cm made of the same acrylic tube as that for the flotation column was used to collect froth. The collar was laid on top of the flotation cell on the platform aligned with the flotation column as shown in Fig. 1 during experiments. The bottom of the collar was attached with a rubber ring using silicon glue to prevent water leakage during froth collection or flotation. Froth arose with aeration and the application of surfactant and gradually filled the collar. The flotation air was shut off after 10 seconds. A circular aluminum disk was inserted into the junctions between the top of the flotation column and the bottom of the collar to collect the froth. A stop watch was used to record the aeration time and the time of froth collection. Froth was collected immediately after the aeration was stopped in the first experiment. The collected froth along with the collar container was weighed. Before starting another flotation experiment, forced air was used to completely destroy the froth produced in the previous experiment.

Furthermore, the suspension was thoroughly stirred to make sure that the fibers were well mixed in the suspension. The above described experiment was then repeated. However, froth collection was not carried out immediately after shutting off the flotation air but was delayed. The delay time was varied in each subsequent experiment to allow the water and fiber to drain within the froth. The froth draining time is defined as the time lapse from the time of stopping the aeration to the time of froth collection. Therefore, the history of the dynamic drainage of water and fibers in the froth can be reproduced through a series of experiments. The entire series of the experiments described above was repeated to obtain duplicates of froth collection at a given delay time. However, the collection experiments were conducted backward, that is, froth collection with the longest draining time was conducted first and the zero draining time was conducted last. When studying spatial fiber fractionation in froth, two acrylic collars with combined height equals to that of the height (13 cm) described above were used. Separate collection of the top and bottom froth was achieved by first inserting a circular aluminum disk into the junctions between the bottom collar and the top of the flotation column immediately followed by inserting another aluminum disk into the junctions between the two collars.

Fiber Characterization and Determination in the Reject Streams

The gravimetric method was used to determine fiber rejection in froth flotation. The wet mass of the collected froth was first determined by a balance. The wet reject was then transferred into a home-made aluminum-foil boat (weight about 6–7 g). Fiber containing froth collected at the same delay time was combined into one boat. Then the boats were put in an oven to remove water and moisture. The oven temperature was set at 105°C. The boat sat in the oven overnight and was removed and weighed for the determination of ovendry fiber in froth. Additional collections were made at selected experimental conditions to obtain fiber suspension samples for fiber length determination by the Kajaani FS-100 fiber analyzer.

RESULTS AND DISCUSSION

Experimental Repeatability

The experimental repeatability of the froth collection process was demonstrated in a previous study [15] by conducting two sets of replicate measurements of water and fiber in froth to reproduce the histories of two draining events under the same experimental conditions. Good experimental repeatability was obtained, which was especially true for water drainage. In this study, we conducted the repeatability of fiber length measurements in sampling and analyzing using the Kajaani FS-100 fiber analyzer. For a given fiber sample collected from froth, five independent measurements were conducted. The standard deviation was then calculated. Figure 2 shows the five measured fiber distributions from a froth sample collected at zero drainage time during TMP pulp flotation. The data clearly show that the repeatability in fiber length measurements was excellent. The coefficients of variation were less than 10% except in the long fiber range (>3.5 mm) where the fiber population was small. The coefficient of variation of the fiber length-weighted mean fiber length was only 3.6%. Similar

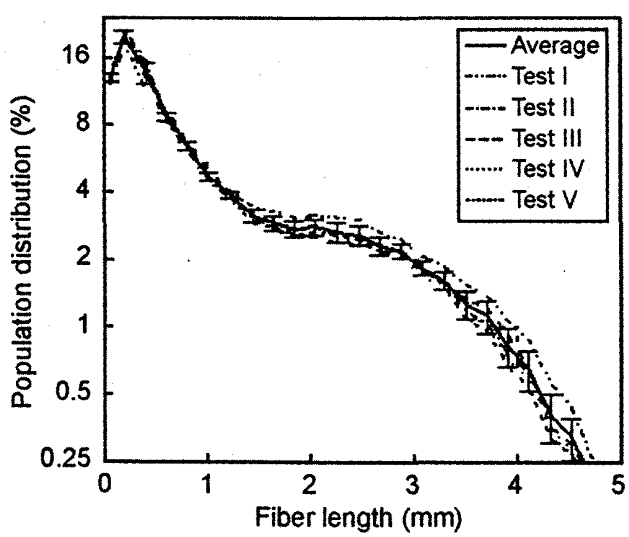

Figure 2. **Repeatability tests of fiber length distribution measurements.**

repeatability was also obtained for fiber samples collected from different froths.

Spatially Averaged Drainage and Water and Fiber

Before discussing the fiber fractionation phenomenon in froth, it is useful to present some general phenomena of water and fiber drainage in flotation froth of fiber suspension. Figures 3 and 4 show the time-dependent water and fiber contents in froths collected at three different vertical locations from the TMP fiber suspension interface. The data clearly show again the dynamic drainage of water and fiber in fiber suspension froth. Similar drainage processes were also observed in froth of kraft pulp suspension. The data also show that water drains faster than fibers. The drainage is fast in froth near to the froth–suspension interface, which

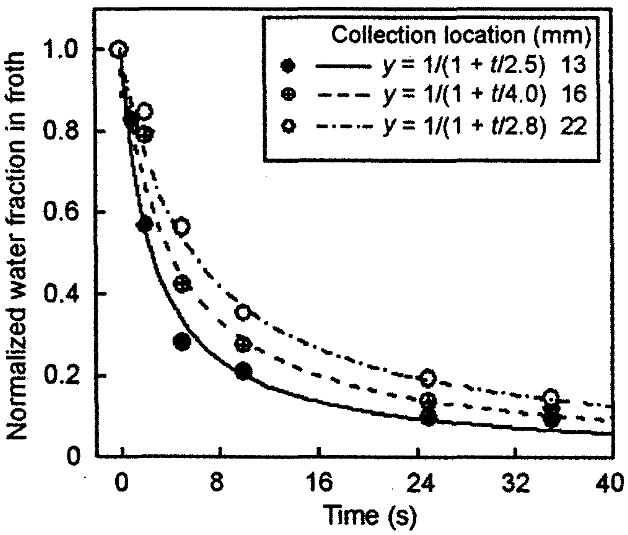

Figure 3. **Temporal evolutions of water content in froths collected at different heights.**

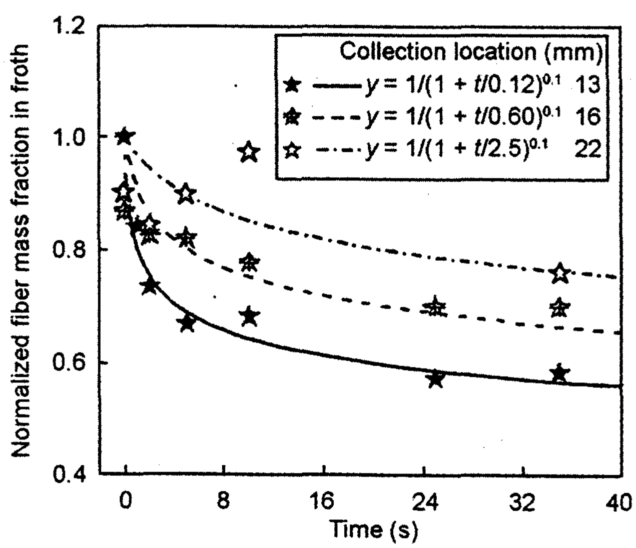

Figure 4. **Temporal evolutions of fiber content in froths collected at different heights.**

is especially true for fibers. Some fibers can be permanently entrapped in froth. The spatially averaged water and fiber drainage can be modeled by an inverse relationship with time according to our previous study [15]. The data presented in Figures 3 and 4 can be used to calculate water and fiber flux in froth as discussed in our previous study [15] to reveal quantitative knowledge about water and fiber drainage in froth of fiber suspension, for example, fiber drainage is caused by water carryover and a critical water flux exists below which fiber drainage stops.

Time-Dependent Fiber Fractionation in Froth

Figure 5 shows the effect of drainage time on the measured length-weighted averaged mean fiber length in the collected froth. The data clearly show the increase in mean fiber length as drainage proceeds for both the TMP (11%) and kraft fiber (4%) suspension experiments. The first data point in each data series in Fig. 5 is the mean fiber length of the original pulp. Significant variation in the mean fiber length from that of the original pulp sample, or initial fractionation, was observed immediately after the beginning of flotation (drainage time = 0, or about 10 seconds for the froth to fill the entire collection collar). The initial fiber fractionation that occurred during the period of froth filling the collar is a result of two processes, i.e., fiber entrainment (or flocculation [2]) and hindered froth drainage by the upward flowing suspension. The results shown in Fig. 5 indicate that initial fiber fractionation was very significant, accounting for 66% of the total fiber length variation (increase) of 11% from the original pulp sample, for the TMP pulp. Figure 5 also shows that the initial fiber fractionation of the kraft pulp was not significant, possibly because of reduced fiber flocculation (meaning uniform entrainment for all fibers) of the short fibers used (length-weighted mean fiber length was only 1.87 mm compared with 2.1 mm for the TMP pulp). The total

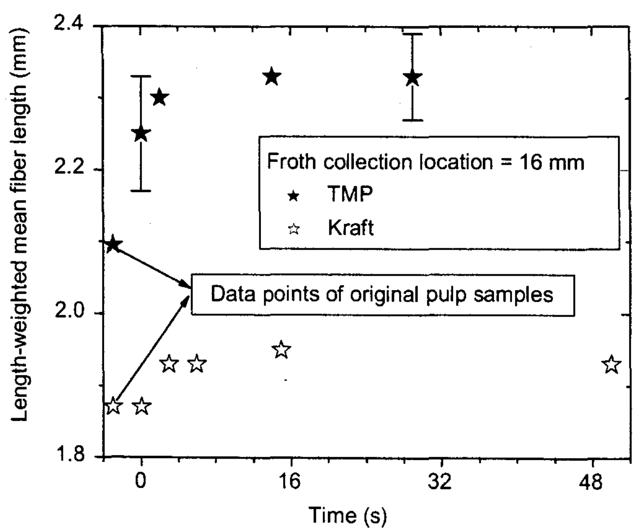

Figure 5. **Effect of drainage time on measured length-weighted mean length of the fibers in the collected froth.**

mean length of the fibers in the froth is only 4.3% longer that of the original pulp.

The secondary fractionation (starting with drainage time > 0) shown in Fig. 5 can be uniquely attributed to froth drainage because fiber entrainment stopped after the aeration was shut off. Therefore, the effect of froth drainage on fiber fractionation postulated by Ajersch and Pelton [2] can be examined using the data with drainage time greater than zero. Figure 5 indicates that froth drainage during secondary fractionation accounts for 34% and almost 100% of the fiber fractionation if measured by mean fiber length for the TMP and kraft pulp, respectively. Wood fibers have very complex morphology and surface properties. The fiber length, shape, surface roughness, geometry, flexibility, etc., can significantly affect the fiber flocculation and hydrodynamics both in suspension and within PB channels of a froth (or froth drainage). Therefore, fiber fractionation of a TMP pulp differs from that of a kraft pulp (Fig. 5). Purely froth-drainage-induced secondary fiber fractionation does not exist in flotation deinking operations. However, the data shown in Fig. 5 provide some measure of the effect of froth drainage in initial fiber fractionation during flotation deinking operations.

Because fiber length is the most easily measurable parameter in fiber analysis, fiber fractionation in froth is further demonstrated by fiber length distribution in this study. Figures 6 and 7 show the time-dependent fiber length distributions of the fiber samples in the collected froths. The mean lengths of the fiber samples were shown in Figure 5. The data clearly show the fiber length fractionation in froth, that is, the relative population of short fibers (<0.8 mm) decreased with the increase in drainage time and as the relative population of long fibers (>0.8 mm) increased in froth. The fiber length fractionation process was very rapid for the TMP suspension. Significant variation in fiber length distribution from the original pulp sample caused by initial fractionation was clearly seen in the increase in number of the long fibers for the TMP pulp (Figure 6). This indicates that flocculated long fibers can be easily entrained, perhaps because of the large bubble size of around 1 cm in the present study, and the floc exclusion mechanism [2] does not apply. The secondary fractionation caused by drainage was also significant especially in the short fiber range (Figure 6), indicating drainage is mainly responsible for the reduction of short fibers and fines in froth. The variation in fiber length distribution was mainly caused by drainage for the kraft pulp and only observed after a drainage time of 3 seconds and the variations were smaller across the entire fiber length range than those observed in TMP suspension froth, which explains the pronounced fractionation in the TMP suspension froth by the mean fiber length data (Figure 5). Examining the fiber length distribution of the original TMP and kraft pulp samples (Figures 6 and 7) indicates that the TMP has a larger proportion of fines (–0.5 mm) than the

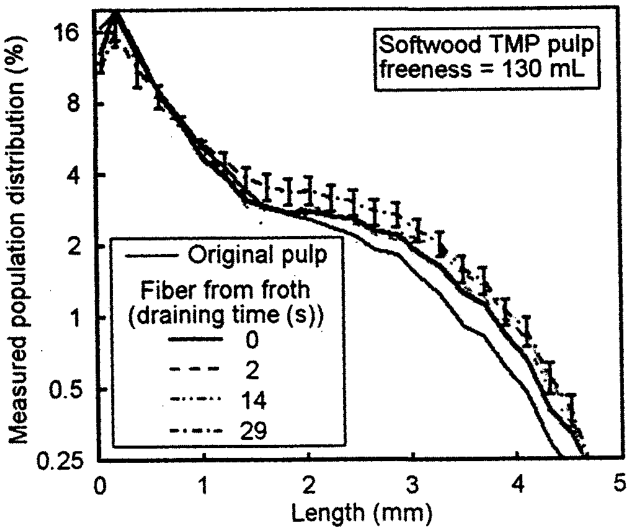

Figure 6. **Effect of drainage time on fiber length distribution of thermomechanical pulp (TMP) fibers in the collected froth.**

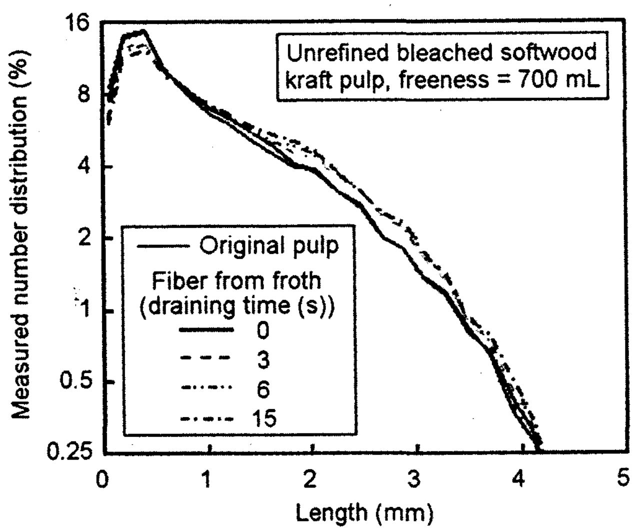

Figure 7. **Effect of drainage time on fiber length distribution of kraft pulp fibers in the collected froth.**

kraft pulp, which contributed to the fast fractionation of the fibers because short fibers are more likely to be drained than long fibers. Because the refined TMP and the unrefined kraft pulp have significant differences in fiber surface properties and the unrefined kraft pulp should have a more favorable hydrodynamic drainage, it seems that the variations in the fiber surface properties have less effect on fiber fractionation or drainage than the fiber length does.

To illustrate the whole fiber fractionation phenomenon, Figure 8 shows the relative deviation of fiber length distribution of fiber samples in froth from their original pulp samples. The results clearly show the decrease in short fibers (fiber length < 0.8 mm) and the increase in long fibers (>0.8 mm). The deviations in fiber distribution are very significant and change almost linearly with fiber length for

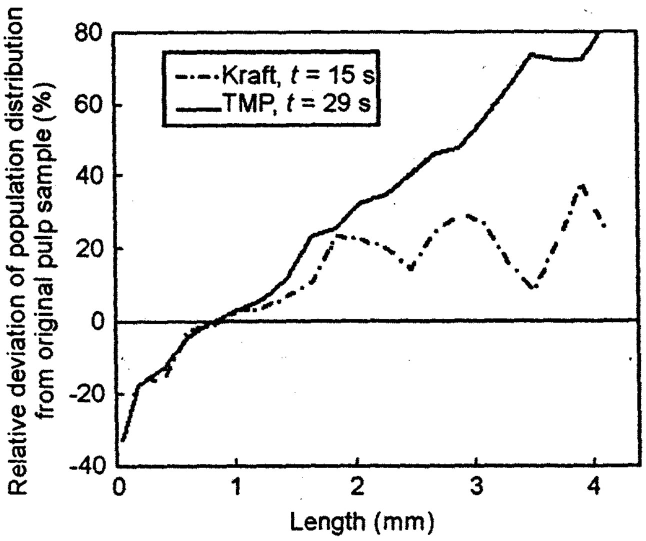

Figure 8. **Relative deviations of fiber length population distribution of pulp fibers in froth collected from the original pulp samples (thermomechanical pulp (TMP)).**

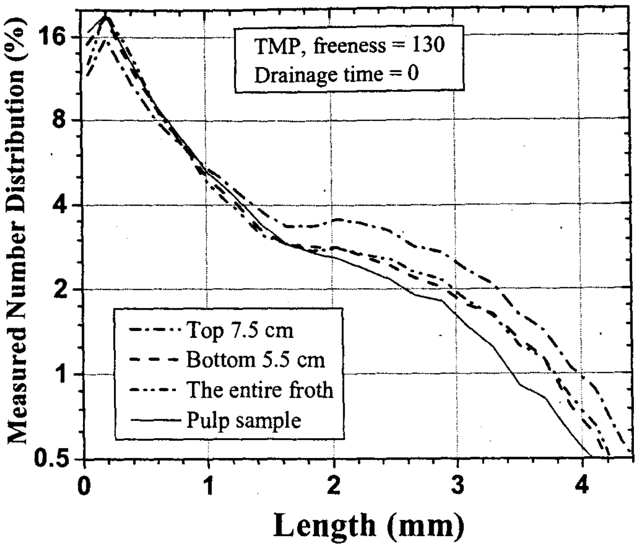

Figure 9. **Fiber fractionation in space: variation in fiber length distribution of thermomechanical pulp (TMP) fibers collected at different froth heights.**

TMP. For example, the relative population of fibers with fiber length around 2 mm is increased by about 30%. Assuming the total fiber loss is about 5%, then the total loss of the number of fibers around 2 mm is 6.5%. The decrease in population distribution reached about 50% for fibers around 3 mm. The population distribution decreased by about 20% for fibers less than 0.3 mm. In other words, the total loss of fibers around 3 mm is about 7.5%, while the total loss of fibers less than 0.3 mm is only 4%. Therefore, flotation rejects more long fibers than short fibers, which agrees with the results observed by Li and Muvundamina [4] and Ajersch and Pelton [2] for the flotation conditions conducted. Similar behavior was also observed for kraft pulp suspension, but it was not as pronounced as that for TMP because the kraft pulp has a smaller proportion of short fibers than the TMP (Figures 6 and 7).

Spatial Fiber Fractionation in Froth

It was also observed that fiber fractionation occurred spatially. Figure 9 shows the fiber length distribution in froths collected from different heights (using two collars as described in the experimental section) compared with the fiber length distribution of the original TMP. The collection was conducted at zero drainage time. Therefore, fiber fractionation observed in the top part of the froth was caused by drainage effect, while the fiber fractionation observed in the bottom part was caused by the combination of the effect of entrainment through the froth and suspension interface and the effect of drainage from the top froth. Fiber fractionation is much more pronounced in the upper part of the froth than in the lower part of the froth, indicating that long fibers are not only difficult to drain, which causes the fractionation phenomenon, but they are even more difficult to drain once they reach the upper part of the froth because of decreased draining water flux [15]. The pronounced effect of fiber fractionation in the top froth again indicates that drainage has a strong influence on fiber fractionation in froth and affects the quality of recovered fibers in flotation deinking operations because ink is removed by removing upper part of a froth that has a high percentage of long fibers compared with the original pulp. Fiber length fractionation in the bottom froth and in the entire froth was essentially the same. This was caused by the fact that only a very small amount of fibers were present in the top froth based on our previous study [15] that has insignificant effect on the fiber fraction of the entire froth.

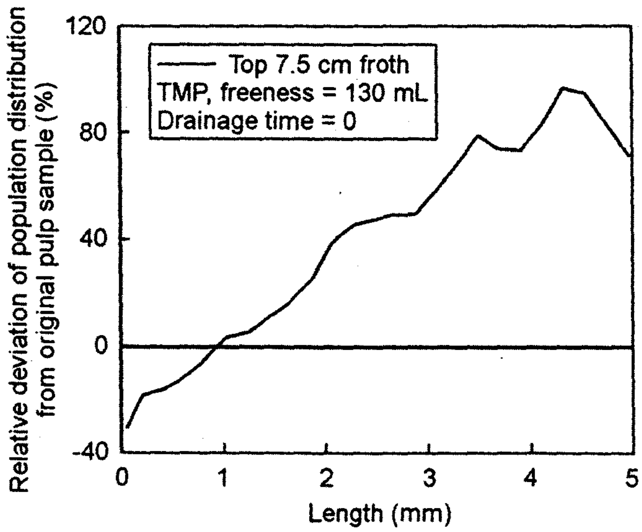

Figure 10. **Relative deviations of fiber length population distribution of pulp fibers from the upper part of a froth from the original pulp sample (thermomechanical pulp (TMP)).**

Figure 10 shows the relative deviation of fiber length population distribution of fiber samples collected in the upper part of the froth from their original pulp samples. Again, the deviations in fiber distribution change linearly with fiber length. The relative population of fibers with fiber length around 2 to 3 mm is increased by about 50%. Assuming the total fiber loss is about 5%, then the total numbers of fibers around 2 to 3 mm is decreased by 7.5% and it can be estimated that the total numbers of fibers longer than 2 mm is decreased by more than about 7.5%, a significant change in fiber quality in terms of length.

CONCLUSIONS

This study experimentally verified fiber fractionation (in terms of fiber length) through flotation. Fiber fractionation is caused by the dissimilarities in fiber flocculation, entrainment, or drainage among fibers of different length or morphology near the suspension and froth interface and within the froth once the fibers are entrained. Fiber flocculation and entrainment are mainly responsible for the entrainment of long fiber into froth, while froth drainage is mainly responsible for the reduction of short fiber and the retaining of flocculated fibers in froth. The numbers of fibers with length around 0.8 mm are proportional to the total numbers of fibers drained. However, the number of fibers with length shorter and longer than 0.8 mm drained disproportionately, that is, more for fibers shorter than 0.8 mm and less for fibers longer than 0.8 mm, compared with the total number of fibers drained. As a result, the fiber length distribution of fibers collected from froth showed a lower relative percentage of fibers less than 0.8 mm and a higher relative percentage of fibers longer than 0.8 mm than those measured in the original pulp sample. The deviation in the relative distribution from the original sample increased linearly with fiber length from -30% at fiber length 0.1 mm to 80% at fiber length 4 mm for the TMP tested after 30 seconds drainage time. As a result, the length-averaged mean fiber length in the collected froth is increased from 2.1 mm in the original pulp sample to 2.4 mm or by 11%. Fiber length fractionation phenomenon was also observed along the froth vertical direction, that is, fiber collected from the upper part of a froth has a relatively lower percentage of shorter fibers, higher percentage of long fibers, and a longer mean fiber length compared with original pulp sample. Similar results were also obtained when experiments were carried out using a kraft pulp sample, but the fractionation is less pronounced probably because of the fact that the kraft pulp used has a small percentage of fines (short fibers). The fiber fractionation phenomenon revealed in this study indicates that flotation deinking not only results in fiber yield loss but also selectively rejects more long fibers greater than 2 mm in length (about 7.5%) than short fibers less than 0.3 mm (only about 4%) compared with the original pulp sample. Assuming the total loss of fibers is 5%, this phenomenon has a significant impact on the quality of recovered fibers.

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