ON FIBER REJECTION LOSS IN FLOTATION DEINKING

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Reducing fiber rejection loss in flotation deinking is very important to conserve natural resources and reduce the cost of secondary fibers in paper recycling. This study examined two aspects of the problem, fiber consistency in the rejection stream and rate of Froth (or wet stream) rejection. Flotation experiments were conducted using both nylon and wood fibers in column and commercial bench-scale flotation deinking cells. It was found that increased froth stability resulted in a lower fiber consistency in the wet reject stream. However, it also increased rejection rate of the wet stream. As a result, the total fiber rejection loss was increased with the increase of froth stability. The results obtained suggest that controlling froth stability through reducing frother application and froth rejection are effective ways to reduce fiber yield loss in flotation deinking. This study also experimentally measured water and fiber drainage in fiber suspended froth to explain the effect of froth stability on fiber consistency in the reject stream using froth drainage dynamics

Il est très important derédutre la perte de rejet de fibres dans le désencrage par flottation afin de conserver les ressources naturelies et de réduire le coût des fibres secondaires dans le recyclage du papier. Dans cette étude, on examine deux aspects du problème : la consistance des fibres dans le courant de rejet et le taux de rejet de mousse (ou courant de rejet humide). Des expériences de flottation ont été menées à l´ aide de fibres de nylon et de bois dans une colonne et dans une cellule de désencrage par flottation commerciale de taille réduite. On a trouvé que l´ augmentation de la stabilité de la mousse diminue la consistance des fibres dans le courant de rejet humide. Toutefols, cela augmente aissi le taux de rejet du courant humide. En conséquence, la perte de rejet de fibres totale augmente avec la stabilité de la mousse. Les résultats obtenus suggèrent que le contrõle de la stabilité de la mousse par réduction de l´ application d'agent moussant et du rejet de mousse est un moyen efficace pour réduire la perte de rendoment de fibres dans le désencrage par flottation. Dans cette étude, on a également messuré de manière expérimentale le drainage de l'eau et des fibres dans une suspension de mousse de fibres pour expliquer l'effet de la stabilité de la mousse sur la consistance des fibres dans le courant de rejet à l´ aide de la dynamique de drainage de la mousse.

Keywords: flotation deinking, paper recycling, secondary fibers, fiber rejection loss, froth drainage

Since its introduction to the industry in the 1980s, the froth flotation process has been widely employed by the pulp and paper industry for removing ink from recovered secondary fibers. In flotation deinking, inks are detached from fibers by the pulping process before flotation. The detached ink particles are hydrophobic in nature and can stick to air bubbles upon colliding with them. Therefore, the detached inks can be removed from the fiber suspension through air flotation by removing the froth produced by aeration and stabilized by a surfactant applied in the pulp suspension. In general, ink removal is increased with increasing froth rejection rate. Unfortunately, the bubble froth rejection process also rejects fibers. Furthermore, the fiber loss increases with increasing froth rejection (Dorris and Page, 1997). Therefore, increased ink removal and increased fiber yield are two contradictory goals in flotation operations.

The mechanism for fiber loss in froth flotation drinking has been well studied and understood. Early studies by Turvey (1987, 1993) indicated that fiber loss was caused by fiber adhesion to air bubbles followed by subsequent removal with the froth. This postulation was challenged by Ajersch and Pelton (1993, 1996) and Ajersch et al. (1992) and most recently by Dorris and Page (1997). They found that the hydrophobicity of a fiber surface does not contribute to fiber loss and that fiber loss is caused by the mechanical entrainment of fibers in the froth. Later, Deng (2000) and Deng and Abazeri (1998). found that

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both physical entrainment of fibers in an air bubble network and adhesion of hydrophobic parts of fiber surfaces to air bubble surfaces contribute to the total fiber loss. However, physical entrainment is the major contributor. They also found that fiber and water losses increased with increase in froth stability. Dorris and Page (1997), Deng (2000), and Deng and Abazeri (1998) also indicated that fiber rejection through froth flotation was linearly proportional to total wet rejection in their studies. Deng and Abazeri (1998) explained that the intercept of a linear correlation of the results represents fibers lost because of true flotation (fibers that were stuck to air bubbles and removed). However, we found that data scatter can be quite significant when solid and liquid reject data were obtained under various experimental and operating conditions, even when the same flotation facility and surfactant were used. Therefore, it remains an unanswered question as to what affects the correlation between fiber rejection and total wet rejection in froth flotation deinking, assuming that the correlation according to Dorris and Page (1997) and Deng and Abazeri (1998) exists.

It is understood that the proportionality constant of the correlation between the wet rejection and fiber (ovendry (OD) base) rejection is the time-averaged fiber consistency of the wet reject stream. It is expected that most flotation operating conditions can affect the fiber consistency of the reject stream because fiber rejection loss is mainly caused by entrainment of fibers in the bubble network of a froth during flotation (Ajersch and Pelton, 1993,1996; Ajersch et al., 1992; Deng and Abazeri, 2000). The Structure of the froth determines the void spaces between bubbles (mainly the space of the Plateau boarder (PB) channels) and can affect fiber entrapment. Both the surfactant and its concentration arid initial bubble size can affect froth structure. Air flow rate, the numbers of bubbles produced per unit time, and the froth stability controlled by the surfactant and its concentration can affect the rate of entrainment. Froth removal method and rate of removal can also affect the fiber consistency in the reject stream. Therefore, only the solid and liquid reject data obtained wider exactly the same experimental conditions can be used for reject consistency determination.

It is also understood that the total fiber (OD base) rejection loss is equal to the fiber consistency in the rejection stream times the total wet rejection, which in turn is equal to the rate of wet rejection times the rejetion time. Therefore, a complete understanding on fiber rejection loss through flotation includes two aspects: (1) the fiber consistency in the rejection stream or in the froth and (2) the rejection rate of froth or the wet stream. To control fiber rejection loss through flotation deinking, it is important to understand the effects of various flotation deinking operating conditions on fiber consistency in the rejection stream as well as the rate of froth rejection in flotation. The objective of this study is to understand these two aspects of the problem through laboratory froth flotation experiments. Because of the importance of reducing fiber rejection loss to the economics of the paper recycling industry and the need to conserve natural resources and protect the environment, this study was undertaken to provide fundamental insights into the issue of fiber rejection loss in flotation deinking.

EXPERIMENTAL

Flotation Cells

A column flotation cell was made in-house using a Plexiglas (Rohm & Haas Co., Philadelphia, PA) tube with an inner diameter of 15.9 cm. The length of the flotation cell is 108 cm. A circular stainless steal porous disk 6.35 mm thick and 15.8 cm in diameter (model SIKA-R 200, GKN Sinter Metals Filters, GmbH, Germany) was mounted at the bottom of the column for aeration. The porosity of the disk was 51% with minimum, maximum, and effective pore diameters of 28, 135, and 65 µm, respectively, which gives an equivalent diameter of 70 µm. To ease froth collection, a stainless steal collar with a platform was mounted at the top of the flotation column. Half the surface 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. Inhouse pressurized air was used for flotation. A pressure regulator and a flowmeter (model FMA-A2317, OMEGA, Stamford, CT) were used to regulate the airflow rate into the column. A pressure of about 0.6 atm (or 608 kPa gage) was set during flotation. A check valve was also installed in the air line to prevent water backflow to the airflow meter.

A bench-scale commercial Denver flotation cell (model 53 3000, Denver Equipment Company, Colorado Springs, CO) was also used in this study. The capacity of the cell was 8 L. The bottom section of the cell was a rectangularly shaped tank, and the two side surfaces were changed to a trapezoid in the up section. The froth reject weir was the up edge of the front surface that connects the two side surfaces. The cell was made of stainless steel. Good mixing of suspension was provided by a motor-driven rotor vertically inserted into the bottom of the center of the tank. The spinning of the rotor also provided aeration of the suspension through entrainment. Ambient air was entrained into the suspension from a hole on one side of the rotor axis, about 35 cm above the bottom of the rotor via a hollow channel along the rotor axis, and flowed though four holes at the bottom of the rotor.

Fibers

Nylon fibers 3 mm long with a diameter of 15 denier, or 43.2 µm, were obtained from Minifibers, Inc. (Johnson City, TN) and used in column experiments. The specific gravity of the nylon fiber is 1.14 g/cm^3. Deinked secondary fibers of mixed old newsprint (ONP) and old magazine (OMG) with a mixture ratio of 9:1 from the accept stream of the pilot plant flotation experiment reported in our previous study (Zhu et al., 2005) was used in the Denver cell flotation experiments. The ONP was from Madison Newspapers, Inc. (Madison, WI), and the OMG was from Quad Graphics (Sussex, WI) The ash (filler and ink) content of the fibers was about 5% (Zhu et al., 2005).

Chemicals

Most of the flotation experiments were conducted using Triton X. 100 (TX-100) anomionicoctylephenyl ethoxylate frother, analytical grade (J. T. Baker Inc.) as a surfactant to stabilize the froth. Fatty acid soap (EKA Chemicals, Marietta, GA) and two other commer- cial chemicals, trade names Lionsurf 5140 (Kemira Chemicals, Kennesaw, GA) and DI700, were also used in this study.

Froth Flotation

A fiber consistency of 0.5% was used for most of the experiments in the column flotation cell and all the experiments in the Denver cell. The airflow rate was varied from 6 to 45 L/min, and the suspension level was about 2.5 cm below the top end of the column in the column flotation experiments. The air suction hole was fully open in operating the Denver cell. No metering device was provided with the Denver cell.

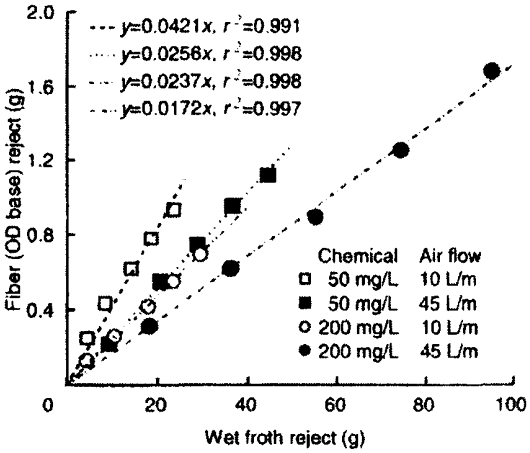

Figure 1. Effect of flotation airflow rate and surfactant concentration on the correlation between the solid (fiber) and liquid (wet froth) rejection during column flotation of nylon fibers.

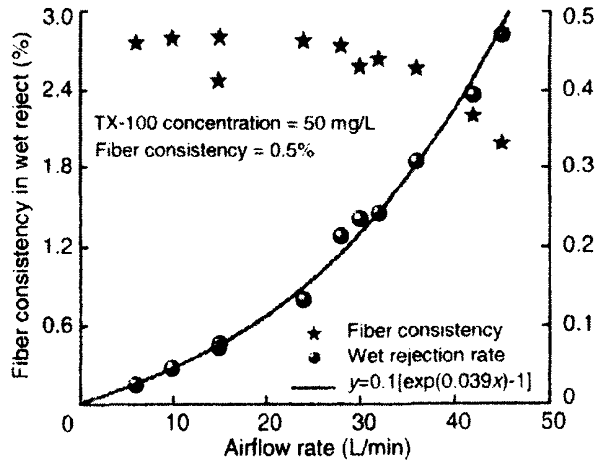

Figure 2. Effect of flotation airflow rate on fiber consistency in the reject stream and wet froth rejection rate in column flotation of nylon fibers.

During column froth flotation experiments, froth rose above the water level and the top end of the flotation column as aeration started. The froth flowed out of the flotation column as a cylindrical shape with minimal deformation. When the froth reached a height of approximately 3.5 cm above the flotation column, the froth was scrapped into a receiver made of aluminum foil using a rectangular piece of Plexiglas. Care was taken during scrapping to make sure that only the froth that rose above the column top was collected and the scrapping step was done at a rapid speed. The froth collection process was repeated for four to five times for each flotation experiment under a fixed set of conditions without interrupting aeration. The same froth height of 3.5 cm in the first collection was used as the criteria to start froth collection for the subsequent collections. A stop watch was used to record the time for the froth to rise from the suspension surface to the top of the flotation column (or about 2.5 cm in height) and the time of the entire collection process of four or five collections. Therefore, the average wet rejection rate could be calculated. A new receiver was used in each collection, arid the initial weight of the receiver was measured by a balance. Before starting flotation under a different aeration rate, 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 because of nylon fiber sedimentation caused by the density difference between fiber and water.

To obtain timedependent free-drainage data of water and fiber in froth, multiple column flotation experiments were conducted under exact operating conditions, but froth collections were delayed for various times after froth reached 3.5 cm high to reproduce the entire froth draining event.

A preset 3.5-minute (or 210-s) flotation time was used in flotation of wood fibers in the Denver cell. The Denver cell was filled with suspension to a level of 8 L for each experiment. With the application of surfactant, froth rose above the rejection weir of the cell and was scrapped into the collection tray of the cell. The reject stream was collected and analyzed in terms of total wet weight (mainly water) and solid (mainly fiber plus a very small amount of ash including filler and ink). Fresh suspension stock was used for subsequent experiment.

Fiber Determination in Reject Streams

The gravimetric method was used to determine fiber rejection in froth flotation. The weight of the aluminum foil receivers ranged from 6 to 9 g, only one order of magnitude larger than the weight of the fibers in the collected froth. The wet reject containing receivers were put in an oven to remove water and moisture. The oven temperature was set at 105°C The receivers sat in the oven overnight and were then removed and weighed. Wet reject collected in the reject tray in Denver cell flotation experiments were weighed and used to make paper pad according to TAPPI method T218 om-91 (TAPPI 1996) for the determination of fiber rejection and consistency in the rejection stream.

RESULT AND DISCUSSIONS

Froth Flotation of Nylon Fibers in Column Cell

Effect of Airflow Rate on Fiber and Wet Stream Rejection

Fiber reject (OD base) was plotted as a function of wet reject from the data obtained in the same column flotation experiment but different collection receivers as shown in Figure 1. Because five Subsequent froth collections were performed under the exact same set of experimental conditions, accumulative fiber and liquid rejection data were plotted for linear regression analysis to obtain fiber consistency in froth (or reject stream); that is, the fiber and liquid rejects of the second data point in Fig. 1 are the summations of the same quantities of the first two collections, and so on. The slope of the plot is therefore the average fiber consistency in the reject stream. Excellent linear correlations between the total wet reject and fiber reject (OD base) were obtained as shown with correlation coefficients greater than 0.99. Figure 1 clearly shows that the fiber consistency in the reject stream varies with surfactant chemical concentration and aeration flow rate in flotation, which explains the significant data scattering in correlating wet reject with solid reject obtained from different flotation conditions. The zero y intercept indicates that all fibers were rejected through entrainment in these experiments of column flotation of nylon fiber suspension. Figure 1 also indicates that a stable froth, resulting from the increase in surfactant concentration in the suspension or the high aeration rate, produced a rejection stream with low fiber consistency. This seems contradictory to common sense in flotation deinking practice because a more stable froth always results in higher fiber rejection loss than does a less stable froth. There are two parameters that control fiber rejection loss in

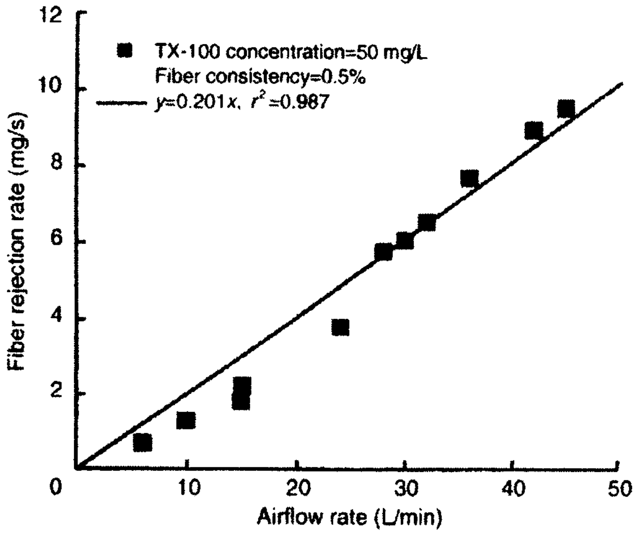

Figure 3. Effect of flotation airflow rate on fiber rejection rate in column flotation of nylon fibers.

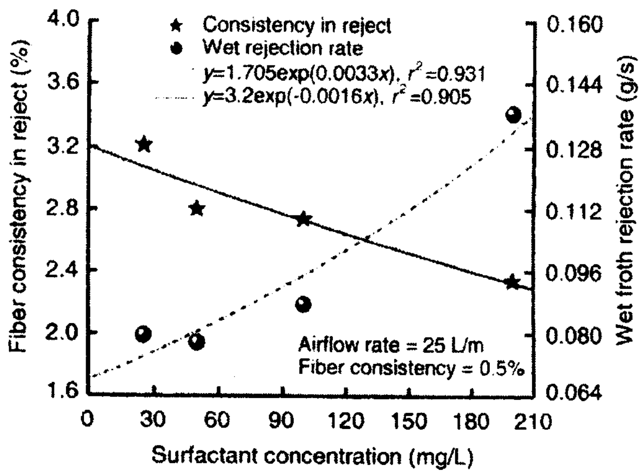

Figure 4. Effect of surfactant concentration on fiber consistency in the reject stream and wet froth rejection rate **in** column flotation of nylon fibers.

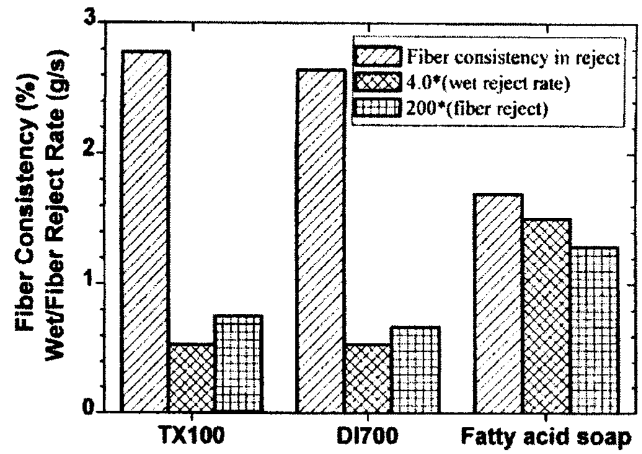

Figure 5. Comparisons of fiber consistency, wet rejection rate, and fiber rejection rate in column flotation of nylon fibers using three different surfactants.

flotation: the total OD fiber rejection loss equals the fiber consistericy (first parameter) in the rejection stream times the total wet rejection (second parameter), which in turn is equal to the rate of wet rejection times the rejection time. In general, a stable froth can not only increase the froth volumetric rejection rate but also increases the mass (wet) rejection rate. To further illustrate the effect of aeration on fiber rejection loss, more experiments were conducted under a wide range of aeration rates. The linear regression procedures to correlate wet reject arid fiber reject discussed previously were applied to the data from this set of experiments. Figure 2 again clearly shows that the fiber consistency in the reject stream decreased with the increase in airflow rate or froth stability. The decrease was slow at low airflow rates and rapid at high airflow rates. It was found that the measured time for the froth to raise 2.5 cm above the suspension increased exponentially, i.e., $t = 140e^{-0045x}$ (r^2 = 0.974) with the decrease in flotation airflow rate, illustrating the effect of airflow rate on froth stability. The data shown in Fig. 2 were obtained in three separate experiments that spanned a 2-week period. The excellent inverse correlation, with the exception of one outlier data point, indicates good repeatability of the experiments.

Figure 2 also shows that the average wet reject rate increased exponentially with the increase in aeration rate. The results shown in Figure 2 indicate that an increase in flotation airflow rate and therefore the froth stability results in a decrease in fiber consistency in the reject stream and an increase of wet froth rejection rate. Figure 3 shows the effect of flotation airflow rate on fiber (OD base) rejection rate from the same set of experiments shown in Figure 2. The results clearly show that the fiber rejection rate increases linearly with the increase in flotation aeration, which agrees with common sense. It can be concluded that the exponential increase in wet froth rejection rate is responsible for the increased fiber rejection loss at high aeration rate (or increased froth stability) in froth flotation.

Effect of Surfactant Concentration on Fiber and Wet Stream Rejection

Another set of experiments were conducted at a fixed airflow rate of 25 L/m while surfactant (TX-100) concentration was varied, that is, 25, 50, 100, and 200 mg/L in the suspension. Again, the fiber consistency in the reject stream decreased with increase in surfactant concentration or froth stability. An exponential decay function fits the data very well (Fig. 4). The wet reject increases exponentially with the increase of surfactant concentration in the suspension or froth stability (Fig. 4). Because the exponential increase in wet reject rate (index = 0.0033) is about two times faster than the exponential decay in fiber consistency (index = -0.0016), the fiber reject rate increases with the increase in froth Stability through increased surfactant concentration in column flotation. Compared with the results shown in Figure 3, the effect of surfactant on fiber rejection loss is more pronounced (exponential function) than that of air (linear function).

Different surfactants were also used to study the effect of surfactants on fiber consistency in the rejection stream through air flotation (Fig. 5). The limited data (three chemicals were used at a fixed airflow rate of 25 L/min and chemical concentration of 50 mg/L) indicate that different surfactants affect fiber rejection loss differently. This is caused by their effect on froth stability and therefore fiber consistency in the reject stream. Fatty acid soap that has high foamability produces a high wet rejection rate and a reject stream with low fiber consistency. This resulted in a high fiber rejection loss, similar to the surfactant concentration effect on froth stability.

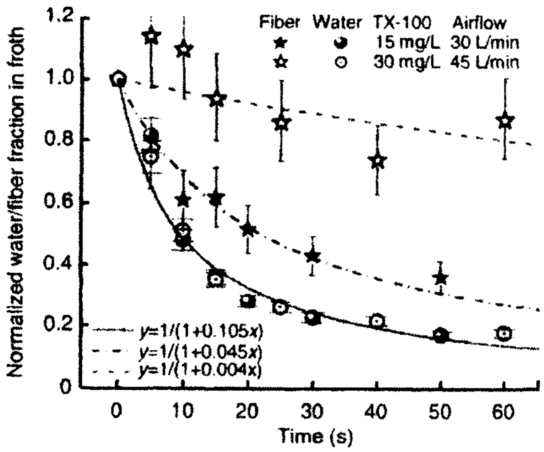

Figure 6. Comparisons of drainage dynamics between water and fiber in a froth under two flotation conditions.

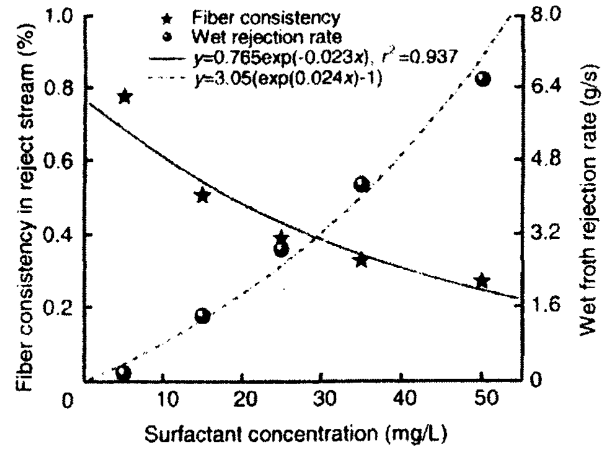

Figure 7. Effect of surfactant concentration on fiber consistency in the reject stream and wet froth rejection rate in bench-scale flotation deinking of wood fibers.

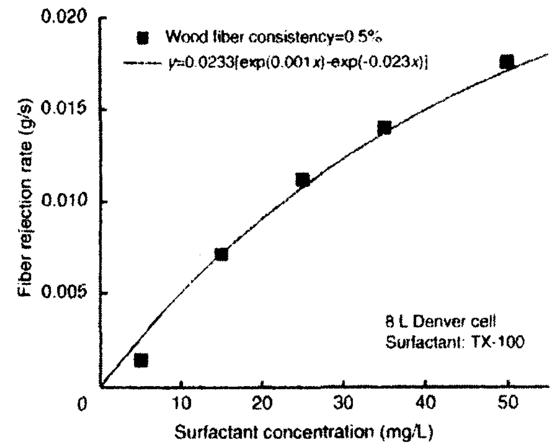

Figure 8. Effect of surfactant concentration on fiber rejection rate in bench-scale flotation deinking of wood fibers.

Fiber and Water Drainage in Froth

The phenomenon reported in Figures 2 and 4 can be explained by froth drainage dynamics (Bhakta and Ruckenstein, 1995; Haas and Johnson, 1967; Koehler et al., 1998; Saint-Jalmes et al., 2000). The liquid phase in the froth is mainly present in the PB channels, formed where the neighboring liquid films formed between the faces of the polyhedral bubbles. The bubbles are stabilized at the top by the surfactant, while liquid flows through the random network of PB channels and accumulates at the bottom. As a result, the liquid fraction in the froth or froth density decreases under gravity, often called free drainage. In this study, the waiting time (for froth to rise) to collect the froth at a low flotation airflow rate was longer than that required at a high airflow rate (increase exponentially with decrease in aeration rate). Therefore, the froth had more time to drain at a low airflow rate than it had at a high airflow rate. Furthermore, the upward liquid dynamic force at a high flotation airflow rate was higher than that at low airflow rate to slow down drainage. As a result, the liquid fraction or the density of a froth, especially in the top part of the froth that was collected as wet reject, obtained at a high flotation airflow rate is higher than that obtained at a low airflow rate. The high liquid fraction in the collected froth yielded low fiber consistency in the wet reject stream. Both theoretical predictions and experimental data in the literature (Bhakta and Ruckenstein, 1995; Haas and Johnson, 1967; Koehler et al., 1998; Saint-Jalmes et al., 2000) indicate that drainage initially increases with time almost linearly then slows down and reaches an asymptotic value, that is, the foam density becomes a constant, when the gravity and capillary pressure force are in balance (Krotov, 1981). Our data obtained at low flotation airflow rates (Fig. 2) indicate that the drainage of the froths had reached equilibrium because of very long waiting periods before the froths were collected. The results in Fig. 2 agree well with the effect of superficial velocity on foam density reported by Haas and Johnson (1967). The time-dependent liquid fraction or froth density derived qualitatively from the fiber consistency shown in Figure 2 and froth rising time ($t = 140e^{0.045x}$) agree with those reported by Bhakta and Ruckenstein (1 995) and Saint-Jalmes et al. (2000). Similar explanation can be made for the effect of increased surfactant concentration on fiber consistency in froth.

One might argue that the aqueous froth drainage dynamics reported in the literature are not sufficient to explain the observed fiber suspension phenomenon in this study because fiber may also drain in the froth. However, we believe that suspended fibers in the PB channels perhaps did not drain as freely as liquid because of friction drag force, fiber flocculation behavior, and capillarity forces, as validated by the free drainage data of water and fiber obtained in the fiber suspension froth in this study. As shown in Fig. 6, fiber drains much slower than water. Water drainage was not significantly affected by flotation conditions, while fiber drainage in froth was hindered significantly with the increase in surfactant concentration and aeration rate caused by increased froth stability for the two flotation experiments conducted. The data in Fig. 6 also indicate that water drainage was not significantly altered by the presence of fiber at the fiber consistency of 0.5% experimented with in this study and can be well predicted by the theoretical inverse relationship with time (Weaire et al. 1987). Therefore, the discussion of aqueous froth drainage dynamics applied to this fiber consistency study is valid. Fiber drainage also follows an inverse relationship with time but at a slow rate or smaller time constant (Fig. 6).

Effect of Suspension Fiber Consistency on Fiber and Reject Stream Rejection

Experiments were also conducted with different fiber consistencies in the suspension. Increasing fiber consistency in the suspension increases the fiber consistency in the reject stream. Regression analysis of the wet and fiber rejection data indicated that the fiber consistexicy in the rejection stream was increased from 3.2% to 8.5% (almost tripled) when the fiber suspension consistency was increased from 0.5% to 1.5% (also tripled), indicating it is linearly proportional to the fiber consistency of thesuspension.

Froth Flotation of Wood Fibers in Commercial Laboratory-Bench Flotation Cell

Flotation experiments using wood fibers were conducted in a Denver flotation cell to verify the discoveries obtained from column froth flotation of nylon fiber discussed previously. Figure 7 shows that the fiber consistency in the reject stream decreases exponentially and wet rejection rate increases exponentially with increase in surfactant concentration. This is very similar to that observed in column flotation as shown in Fig. 4. A zero intercept in wet rejection rate at zero concentration was observed (Fig. 7). The fiber rejection rate can be calculated and was found toincrease exponentially withincreasein surfactant concentration (Fig. 8).

Results similar to those shown in Figs. 7 and 8 were obtained when flotation deinking experiments were conducted using a commercially blended deinking chemical Lionsurf 5140 and fatty acid soap. As discussed previously, different deinking chemicals affect fiber consistency in the reject stream differently. This is mainly caused by their effect on froth stability and froth structure. Their influences on wet reject rate also differ.

CONCLUSIONS

This study delineated fiber rejection loss in froth flotation into two aspects of the problem: (1) fiber consistency in the reject stream and (2) the rate of wet froth (or liquid) rejection, Results from air flotation of nylon fibers and wood fibers in a column flotation cell and a commercial laboratory bench-scale flotation cell, respectively, indicate that fiber consistency in the reject stream decreases with increase in froth stability through increased flotation aeration, increased surfactant concentration, or using high foamability surfactant. The reduction of fiber consistency in the reject stream with the increase of froth stability can be explained using froth drainage dynamics in PB channels; that is, an increase in froth stability increases the froth liquid content because of shortened liquid draining time in the froth before collection into the reject stream. This resulted in low fiber consistency in the rejection stream because fibers drain less freely than liquid does in PB channels. However, an increase in froth stability results in an exponential increase in wet froth production or rejection rate. This is responsible for the increase in fiber rejection rate, which is equal to the product of fiber consistency in the reject and the wet rejection rate. It was found that the fiber rejection rate increased linearly with the increase of flotation airflow rate and increased exponentially with the increase of surfactant concentration. The study also revealed that fiber consistency in the reject stream also increases linearly with increase in the fiber consistency of the suspension under flotation.

This study also conducted the first experimental work of water and fiber drainage in fiber suspended froth and demonstrated that fiber drainage is slower than that of water. Water drainage was not significantly affected by the presence of fibre at. a low consistency of 0.5%. The free drainage of water and fiber follows the theoretical inverse relationship with time The fiber drainage study supports the use of froth drainage dynamics to explain the effect of froth stability on fiber consistency in the reject stream.

The results from this study suggest that paper recycling mills should actively control froth stability by reducing frother application as much as possible to reduce fiber yield loss. Mills should also control froth rejection through either mechanical scrapers or suction shoes to reduce fiber yeld loss

ACKNOWLEDGMENTS

The authors acknowledge Mr. Chester Filipowicz for his contribution in the design, fabrication, and modification of the two flotation systems used in this study

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Manuscript received May 13, 2004; revised manuscript received November 17, 2004; accepted for publication January 5, 2005.