Monitoring Liquid and Solid Content in Froth Using Conductivity

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ABSTRACT

This study reports the feasibility of monitoring liquid and fiber rejection during froth flotation of fiber suspensions through conductivity measurements of the rejected froth. The technique was demonstrated in laboratory flotation experiments using nylon and wood fiber suspensions in two laboratory flotation cells. We found that both the total wet rejection and the fiber/solid consistency in the rejection stream correlate well to the measured relative conductivity of the rejected froth. Therefore, the relative conductivity of the froth can be used to monitor the liquid and fiber/solid content in froth. A conductivity sensor can be developed to monitor fiber, filler/ash, and wet/water rejection in flotation experiments. The immediate application of the conductivity technique described in this study is to monitor wet and fiber/solid rejection in industrial flotation deinking operations.

KEYWORDS

Conductivity sensor, Deinking, Fiber loss, Flotation, Froth conductivity, Froth control, Froth drainage, Paper recycling, Reject control.

INTRODUCTION

Since its successful introduction to the pulp and paper industry in the 1980s, the flotation process has been widely used in paper recycling to separate contaminants such as inks from fibers, thereby recovering secondary fibers. In flotation deinking, ink is removed through the rejection of froth. Ink removal is increased with the increase of froth rejection rate in general. Unfortunately, because of the phenomenon of fiber entrainment into the bubble network, the froth rejection process also rejects fibers [1-3]. Furthermore, fiber rejection is increased with increased froth rejection [4, 5]. Reduced fiber rejection in flotation deinking is very important to conserve natural resources and reduce the cost of secondary fibers in paper recycling. Online monitoring of fiber rejection is a prerequisite to achieving process control for the reduction of fiber rejection in flotation deinking. It can also help to improve understanding of the effect of various operating parameters on fiber rejection in flotation, thus optimizing the process.

Capacitance has been used to determine foam density [6]. Conductivity has also been used to measure liquid fraction in aqueous foams [7, 8]. Lemlich [9] related the aqueous foam conductivity (σ_{froth}) to the volumetric liquid fraction ϕ_l by a factor of one third; $\sigma_{froth} = \phi_l/3$. Phelan et al. [8] later developed a more accurate relation between aqueous foam conductivity and the volumetric liquid fraction of foam. These studies indicate that it is conceivable in flotation deinking or mineral extraction applications to use conductivity to monitor the liquid content in froth associated with air flotation. On the other hand, the rejection of solid (fiber, ash, filler, etc.) through froth removal was found to be linearly proportional to total wet (liquid and solid) rejection in flotation deinking studies [4, 5]. Based on past research on aqueous foam conductivity and on the correlation between rejected solid and liquid through froth removal in flotation deinking, this study demonstrated the feasibility of using conductivity to monitor fiber and liquid content in flotation deinking froth. The underlying hypotheses of our proposed technique are as follows: (1) The Lemlich theory or a modified form of the relation between froth conductivity and froth liquid fraction can be found in flotation froth that contains solids, such as fibers, filler, and ash. (2) Each flotation parameter (surfactant, aeration) that affects froth stability, production, liquid fraction, and therefore conductivity, has a monotonic relation with froth conductivity when other parameters are fixed. The effect of the flotation parameter on froth production can therefore be measured by froth conductivity. (3) The established

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relations between the froth liquid fraction and froth production with froth conductivity can be used to monitor (by froth conductivity measurements) the rejections of liquid (wet) and solid (fiber, etc.) during froth removal in air flotation.

This study experimented in laboratory bench scale flotation cells as the first step to develop a conductivity sensor to monitor liquid, solid, or fiber rejection in flotation deinking operations. Initial feasibility was demonstrated using an aqueous nylon fiber suspension in a column flotation cell. Flotation of partially deinked pulp (to avoid potential complications from stickies, filler, and inks) was then conducted using a commercial bench scale Denver flotation cell. Results from these experiments showed remarkable success of the proposed conductivity technique. Future work to study the performance of the conductivity technique in real flotation deinking systems is warranted.

THEORY

Lemlich [9] derived the following theoretical equation to relate aqueous froth (liquid and gas only) liquid volumetric fraction (ϕ_1) to froth relative conductivity (σ_{froth}) based on Plateau Border (PB) froth structure:

$$\sigma_{froth} = \phi_l/3 \qquad (1)$$

where the froth relative conductivity, σ_{froth}, is defined by the conductivity of the froth divided by the conductivity of the liquid.

Liquid rejection rate through froth removal, R_L, same as wet rejection for aqueous froth, R_w, can be expressed as the product of liquid volumetric fraction (ϕ_1) and the volumetric rate of froth rejection (proportional to froth production): R_{froth},

$$R_L = R_W = \phi_l \cdot R_{froth} = 3 \cdot \sigma_{froth} \cdot R_{froth} \qquad (2)$$

Equation (2) clearly states that froth conductivity can be related to the liquid (wet) rejection rate and the volumetric rate of froth rejection.

In flotation deinking, fiber (or any solid) rejection can be easily expressed as the total wet rejection times the fiber (or solid) consistency (χ_{fib}) in the rejection stream:

$$R_{fib(solid)} = \chi_{fib(solid)} \cdot R_L \qquad (3)$$

Therefore, fiber rejection rate can also be related to froth conductivity according to Equations (2) and (3). To successfully monitor wet and fiber rejection in froth flotation, it is necessary to know the fiber consistency in the rejection stream and the froth volumetric rejection (or production) rate. It is often difficult to measure froth volumetric production rate in a practical environment because of the unstable nature of foam. Current research indicates that operating conditions, especially the flotation aeration rate and the surfactant and its concentration, affect froth production or rejection rate: $R_{froth} = R_{froth}$ (*surfactant, aeration, etc.*). Furthermore, these operating conditions also affect froth conductivity. For example, increased surfactant concentration or aeration will result in high froth production and froth with high liquid fraction and therefore high conductivity. We can assume that a monotonic correlation between froth conductivity and each operation parameter exists when the other operation parameters are fixed; for example,

$$\sigma_{froth} \propto f'(aeration) \qquad (4a)$$
$$\sigma_{froth} \propto g'(surfactant) \qquad (4b)$$

All other flotation conditions except for aeration (Eq. (4a)) and surfactant (Eq. (4b)) were fixed. Moreover, functions f' and g' are monotonic so that their inverse functions $f_a(\sigma_{froth})$ and $g_s(\sigma_{froth})$ exist and are unique. Therefore, each independent variable (operating parameter) that controls froth production can be substituted by conductivity when the other variables are fixed. Therefore,

$$R_L = 3 \cdot \sigma_{froth} \cdot R_{froth}(aeration, surfactant, etc)$$
$$\propto \sigma_{froth} \cdot R_{froth}[f_a(\sigma_{froth}), g_s(\sigma_{froth}), etc] \qquad (5)$$

As revealed in our previous studies, the fiber consistency in the reject stream was mainly affected by the drainage of liquid (water) [10] and fiber to some extent (fiber drainage is caused by water carryover [10]) through the Plateau Border channels for a given fiber consistency of the flotation suspension. Therefore, fiber consistency in froth can be measured by the froth conductivity; for example,

$$\chi_{fib} \propto j(\sigma_{froth}) \qquad (6)$$

Substitute Equations (5) and (6) into Equation (3),

$$R_{fib} = \chi_{fib} \cdot R_L$$
$$\propto \sigma_{froth} \cdot j(\sigma_{froth}) \cdot R_{froth}[f_a(\sigma_{froth}), g_s(\sigma_{froth}), etc] \qquad (7)$$

Equations (5) to (7) illustrate the underlying theory of our conductivity technique for monitoring liquid and fiber (solid) rejection in froth flotation. Therefore, the hypotheses proposed in the Introduction were supported by the theory. Specifically, fiber and liquid rejection can be measured through the measurements of the conductivity of the rejected froth. Calibration functions of j and R_{froth} can be established through experiments according to Equations (5) to (7) for the determination of liquid and fiber content in a rejection stream in froth flotation. For example, the aeration rate is

fixed in most flotation deinking experiments. In the Denver cell flotation experiments conducted in this study, we found that g_s can be approximated by a linear function and j can be approximated by an exponential and R_{froth} by an exponential decay function.

Fiber consistency is around 1% in flotation deinking and negligible in wet rejection calculation. The filler content was zero in column cell and about 5% (also low) in the Denver cell in this study. Therefore, the liquid and wet rejection and solid and fiber rejection can be used interchangeably. We only calculated wet and total solid (not pure fiber) rejection throughout this study. The rejections of fiber and filler were not separately calculated in flotation of wood pulp. The rejection of filler, ash, or minerals is also of great interest in flotation. Equation **(6)** and hence Equation (7) can be equally applied to those solid materials that are hydrophilic in nature, and their rejection through froth removal is due mainly to water carry over. Therefore, the conductivity technique developed in this study has broad industrial applications other than flotation deinking.

EXPERIMENTAL

Conductivity Probe

We constructed a conductivity probe with two platinum wires 0.36 mm in diameter and 3.2 cm long as the sensing electrodes. The two wires, with a center distance of 7 cm, were supported by an acrylic frame as shown in Figure 1. The center of the frame was cut out to allow froth to rise through the probe. Four brass legs 3.2 mm in diameter and 3.2 cm long were mounted in the comers to both support and align the probe relative to the flotation column described later in the flotation cell section. Signal extension wires were clamped to the platinum sensing wires in the acrylic frame. The probe was connected to a conductance meter (model 35, Yellow Springs Instrument Co., Yellow Springs, Ohio). A model IQ Vma data logger, (Measurement Computing, Middleboro, Massachusetts), was connected to the analog output of the conductance meter to record readings during experiments. Therefore, the probe measured the conductance of the medium with a length of 3.2 cm (the wire length) and depth of 7 cm (the wire separation distance) between the two wires when the probe was submerged into a medium. When the probe was applied to an aqueous foam or solid-containing liquid foam, measured conductivity was the average conductivity of the medium within the described dimension, which correlates to the volumetric liquid fraction of the foam according to Lemlich [9]. This is because the liquid in the void spaces of the air bubble network contribute to the conductivity of the foam medium. A dry foam (less liquid) is less conductive and a wet foam (more liquid) more conductive. Different designs can be made for different applications. The conductivity probe was calibrated using a standard aqueous electrolytic solution of potassium chloride, KCL 7447-40-7 (Cole-Parmer Instrument Company, Vernon Hills, Illinois). Excellent linear response was obtained.

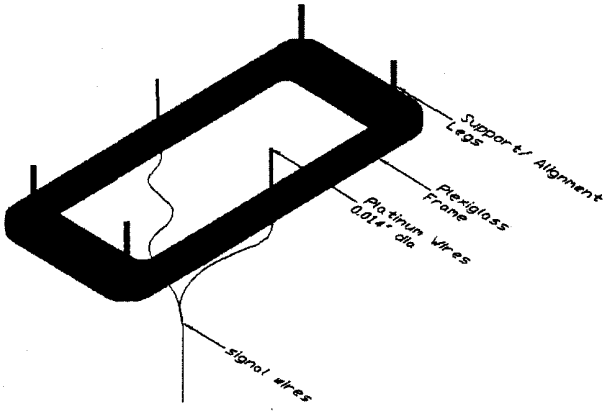

Figure 1. **A schematic diagram of the conductivity probe used in this study.**

Flotation Cells

A column flotation cell as shown in Figure 2 was made in-house with an acrylic tube 15.9-cm inner diameter and 108 cm long. A circular stainless steel 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%. The minimum, maximum, and effective pore diameters of the disk were 28, 135, and 65 µm, respectively, which gives an equivalent diameter of 70 µm. A stainless steel collar with a platform was mounted at the top of the flotation column to collect froth. Half the surface of the platform was

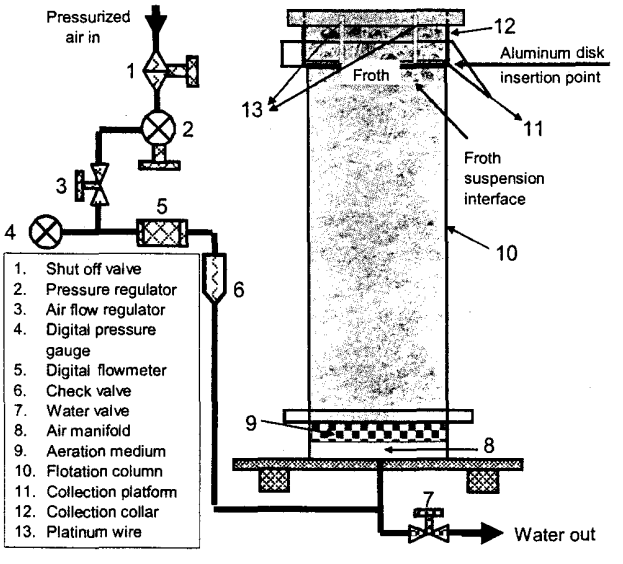

Figure 2. **A schematic diagram of the column flotation cell with the conductivity probe.**

level with the top end of the flotation cell, and the other half was in an inclined channel so that froth can be easily collected. 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 0.6 atm (or 9 psig) was set during flotation. A check valve was also installed in the air flow line to prevent water backflow to the air flowmeter.

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

Fibers

In column flotation experiments, nylon fibers 3 mm long with a diameter of 15 denier or 43.2 μm obtained from Minifibers, Inc. (Johnson City, Tennessee) were used. The specific gravity of the nylon fiber is 1.14 g/cm^3. In Denver cell flotation experiments, partially deinked secondary fibers of mixed old newsprint (ONP) and old magazine (OMG) with a mixture ratio of 9:1 was used to avoid potential complications in conductivity measurements caused by the stickies, fillers, or inks. The pulp was obtained from the accept stream of pilot-plant flotation experiment reported in our previous laboratory. study [11]. The ONP was from Madison Newsprint Company, Madison, Wisconsin, and the OMG was from Quad Graphics, Sussex, Wisconsin. The ash (filler and ink) content of the fibers was about 5%.

Chemicals

Most of the flotation experiments were conducted using Triton X-100 (TX-100), an analytical grade nonionic octyl phenyl oxyethylenic surfactant (Advance Scientific and Chemical, Inc., Fort Lauderdale, Florida), to stabilize froth. The TX-100 concentration varied from 50 to 200 mg/L in the suspension. Either fatty acid soap (EKA Chemicals, Marietta, Georgia) or Lionsurf 5140 (Kemira Chemicals, Kennesaw, Georgia) was also individually used in this study. The application dosage of these chemicals is indicated in Figures 3–10.

Measurement of Froth Conductivity and Collection of Froth Reject - Column Cell

A fiber consistency of 0.5% was used for most of the experiments in the column flotation cell. The airflow rate varied from 6.6-42 L/min, and the suspension level was about 2.5 cm below the top end of the column in the column flotation experiments. The fiber suspension was spiked with about 1.2 g potassium chloride to increase suspension conductivity and improve sensitivity of conductivity measurements. The suspension conductivity was around 650 μmhos after potassium chloride was added. To validate the Lemlich theory [9] (Eq. (1)) in fiber (solid) suspension systems (hypothesis (1) in the Introduction), real time measurements of the froth sample volume and weight (for volumetric liquid fraction calculation) and the representative conductivity of the sample froth are required. We used a 4.45-cm tall cylindrical collar made of the same acrylic tube as that used for the flotation cell to collect froth samples. We used this method to ease real time sample volume determinations because of the meta stable nature of froth. The collar was laid on top of the flotation cell 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. A circular aluminum disk about 20 cm in diameter was used to collect froth along with the acrylic collar. With the application of surfactant, froth rose with air flotation and gradually filled the collar after aeration began. The filling rate depended on the air flow rate and the surfactant and its concentration. A stop watch was used to record the filling time. During the froth-filling period, the conductivity probe was laid on top of the collar and oriented so that the two platinum wires were vertically inserted into the froth in the direction of the air and froth flow movement. Therefore, when the platinum wires of the probe were completely submerged by the froth, the measured conductivity was a good representation of the conductivity of the froth to be collected. When the collar was completely filled with froth, the aluminum disk was immediately inserted into the joint between the collar and the flotation cell, and the disk and the collar were removed. Conductivity was recorded and the conductivity probe removed from the collected froth, which was then weighed by a balance. The volumetric liquid content in the froth can thus be calculated from the volume of the collar and the mass of the water in the collected froth.

Additional trials in the column flotation cell were conducted to determine the correlations between froth conductivity and wet fiber reject (mainly water plus a very small amount of fiber), and fiber consistency of the reject stream. More specifically, these trials determined the functionality of Equations (5) to (7) for probe calibration (hypotheses (2) and (3) in Introduction). In this set of trials, the acrylic collar was not used for froth collection because froth liquid volumetric fraction (or froth volume) is not of interest in

Equations (5) to (7). Furthermore, large errors in gravimetric measurements of fiber rejection in the froth rejection stream can be avoided because the collar weighed about 400 g (three orders of magnitude of the fiber mass of less than 1 g) in the collected reject stream. The conductivity probe was oriented in the direction of air bubble or froth movement as in the previous trials but was supported by the four legs of the probe's acrylic frame and sat on the platform of the flotation column. The legs of the acrylic frame of the conductivity probe were about 3.2 cm long, approximately equal to the length of the platinum wire of the conductivity probe, so the tip of the platinum wire was level with the top of the flotation column. The froth rose above the water level and the flotation column platform as aeration started. The froth flowing out of the flotation column retained a cylindrical shape with minimal deformation. When the platinum wire was completely submerged by the froth, the conductivity reading was recorded and the froth out of the column was scraped into an aluminum foil collector using a rectangular acrylic plate 0.6 cm thick, 16 cm wide, and 16 cm tall. Care was taken to make sure that only the froth that rose above the column top was collected. Samples were collected immediately after each conductivity reading was taken; the conductivity probe was then removed. The weights of the aluminum-foil collectors ranged from 6 to 9 g, or only one order of magnitude larger than the weight of the fiber in the collected froth. The froth collection process was repeated four to five times for each flotation trial under a fixed set of conditions (for example, the same air flow rate, surfactant concentration, fiber consistency) without interrupting aeration. The conductivity reading obtained in the first trial was used as the basis for starting subsequent froth collections. A stop watch was used to record the collection time and the length of time for the froth to rise from the suspension surface to the flotation top end. A new collector was used each time, and the weight of the empty collector was measured for gravimetric determination of water and fiber rejection. Before starting flotation under a different set of operating conditions, forced air was used to completely destroy the froth after each flotation trial. Furthermore, the suspension was thoroughly stirred to disperse the fiber, thus assuring uniform fiber suspension.

Measurement of Froth Conductivity and Collection of Froth Reject - Denver Cell

To further demonstrate the applicability of our conductivity technique for monitoring liquid (wet) and fiber (solid) reject in flotation deinking process, trials were also conducted using a Denver commercial bench-scale flotation cell. Partially deinked secondary fibers consisting of ONP and OMG were used to make a fiber suspension of 0.5% consistency. The conductivity probe was placed horizontally with one side held up on a stainless steel wire hooked to the two sidewalls of the flotation cell and the other side resting on the weir of the rejection port so that the platinum wires were vertically oriented into the froth during flotation. The tips of the two platinum wires were about 1 cm above the suspension level in the Denver cell to keep them from directly contacting the suspension during flotation, when the water level was raised by aeration and flow turbulence. With the application of surfactant, froth rose to completely submerge the conductivity probe. The conductivity of the froth was recorded in real time through a laptop computer at a frequency of 0.25 Hz. During the preset 3.5 min (or 210 s) of flotation, the water level rose initially by aeration and then decreased because of froth rejection. The measured froth conductivity also shows similar behavior. Figure 3 shows the measured time-dependent froth conductivity using TX-100. The conductivity data measured in the first 20 s were not reported because of the transient behavior experienced during the start-up period. The variation of the measured conductivity with time was not significant at a low surfactant concentration because of low gas hold up and less froth rejection.

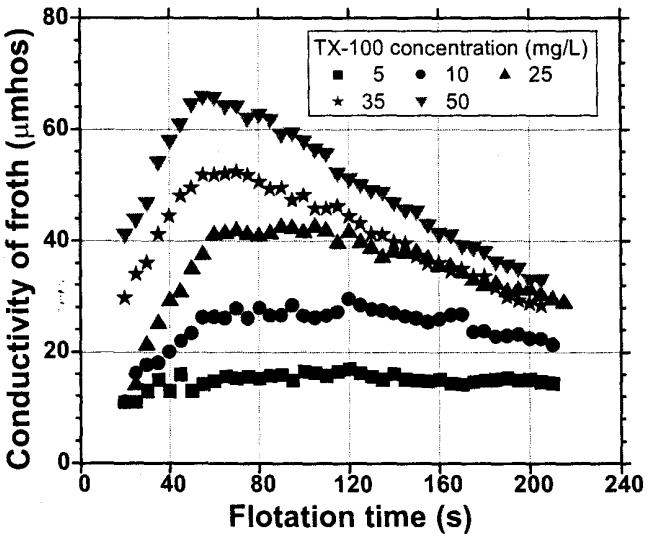

Figure 3. **Measured time-dependent froth conductivity during flotation deinking of wood fibers in the Denver flotationcell.**

Determination of Fiber in the Reject Streams

A gravimetric method was used to determine wet fiber (solid to be specific) rejection in froth flotation. Wet reject collected in the aluminum-foil boat was first weighed and then put in an oven set at 105°C to remove water and moisture. The boat sat in the oven overnight and was then removed and weighed again. Wet reject collected in the reject tray in Denver cell flotation experiments was weighed and used to make a paper pad according to TAPPI method T218 om-91 [12] for the determination of fiber rejection and consistency in the reject stream.

RESULTS AND DISCUSSION

The relative conductivity of the froth, the froth conductivity divided by the conductivity of the aqueous suspension, was required in Lemlich's theory [9] and in Equations (5) to (7) in this study; therefore, conductivity refers to froth relative conductivity from here on.

Hypothesis (1): Froth Conductivity to Monitor Liquid Fraction in Solid Containing Froth-Column Cell

Figure 4 shows the measured water volumetric content in froth as a function of the relative conductivity of the froth. The data were obtained from 48 different experiments conducted under a wide range of air flow rates, surfactant concentrations, fiber consistency, and initial suspension water levels. Experimental data were obtained from trials conducted on different days, spanning about two weeks. Data scatter is not significant. The data follow one universal trend: the relative conductivity of the froth is linearly. proportional to the volumetric water fraction within the froth. A linear regression analysis indicated that the proportionality constant is equal to 0.332 with an r^2 value of 0.956. The value of 0.332 is only about 0.4% less than the theoretical value of one third in the Lemlich relation [9]. The results in Figure 4 indicate that the Lemlich relation between froth conductivity and liquid volumetric content in the froth is valid for froth containing fibers in the fiber consistency range of 0–2%. Therefore, hypothesis (1) in the Introduction was validated.

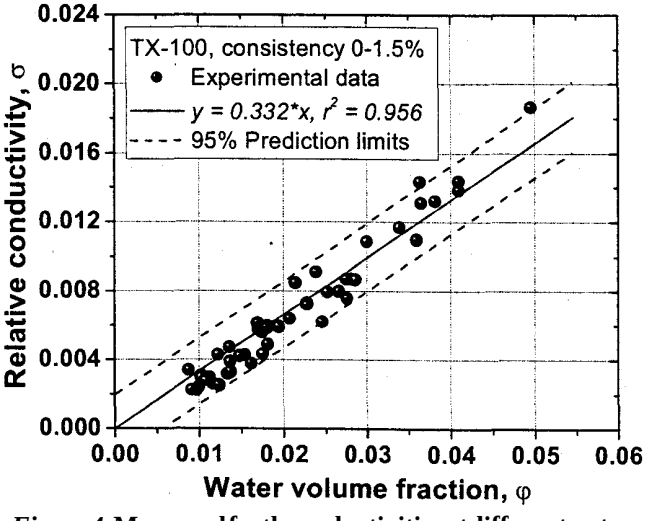

Figure 4. **Measured froth conductivities at different water volumetric contents of fiber-laden froth.**

Hypothesis (2): Froth conductivity to measure froth productivity - Column and Denver Cell

Figure 5 shows the effect of each flotation parameter (aeration rate, surfactant and its concentration, fiber type) on measured froth conductivity. We experimented with three different surfactants. The data were obtained in the column cell using nylon fibers and the Denver cell using wood fibers, varying only one parameter (surfactant, surfactant concentration, aeration rate) with the remaining flotation parameters fixed. The results were plotted in log-log scale to fit all four data sets in the same graph. Figure 5 clearly shows a monotonic correlation exists between froth conductivity, and each flotation parameter (aeration and surfactant concentration) validating our hypothesis (2). Functions $f_a(\sigma_{froth})$ and $g_s(\sigma_{froth})$ are monotonic; therefore, the effect of each flotation parameter on froth production can be represented by froth conductivity. The results also suggest that functions $f_a(\sigma_{froth})$ in Equation (4a) and $g_s(\sigma_{froth})$ in Equation 4(b) can be approximated by linear (monotonic) functions.

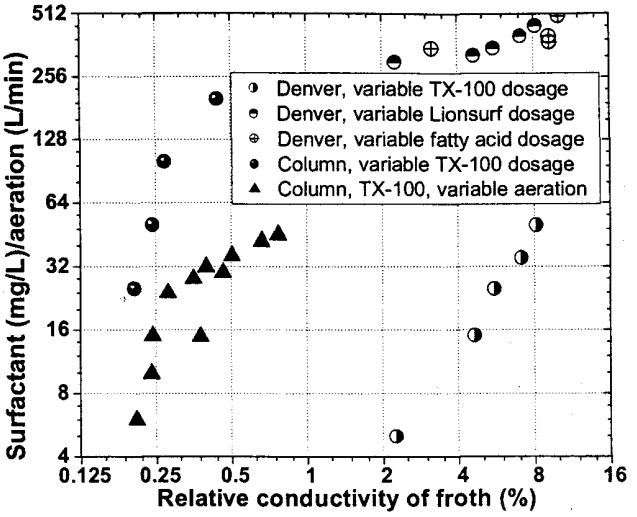

Figure 5. **Monotonic correlations between each flotation condition (surfactant concentration or aeration rate) and measured relative froth conductivity obtained in the column and Denver cell.**

Figure 6 shows the froth production rate as a function of froth relative conductivity to validate Equation (5). The data were obtained in the column flotation cell, and the froth was collected by the cylindrical collar so that the froth volumetric production rate can be calculated. Monotonic relation between froth volumetric production rate and froth relative conductivity was experimentally verified for both variable aeration and surfactant concentration. The results in Figure 6 further validate the hypothesis (2): "The effect of each flotation parameter on froth production can therefore be measured by froth conductivity."

Hypothesis (3): Froth Conductivity for Monitoring Liquid and Fiber in Froth - Column Cell

Effect of Aeration Rate

Aeration rate varied from 6.6 to 42.0 L/min at a fixed surfactant (TX-100) concentration of 50 mg/L in the suspension. The wet reject and fiber consistency in the

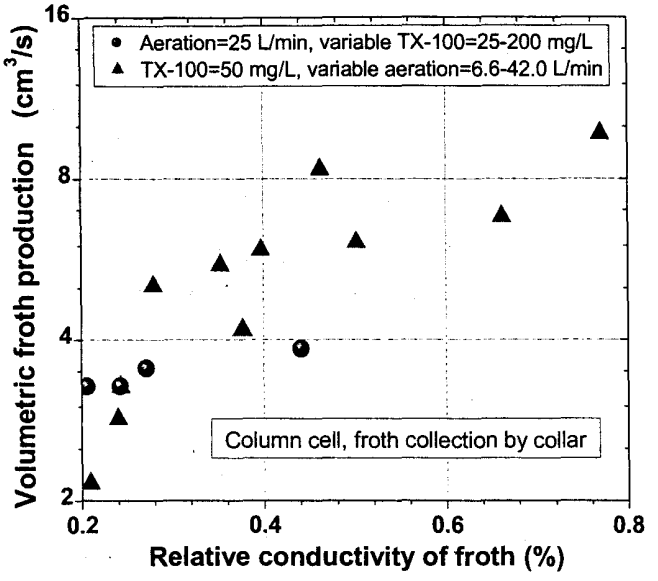

Figure 6. **Froth production as a monotonic function of froth conductivity obtained in the column cell for varying aeration rates and surfactant concentration.**

reject stream was plotted against the relative conductivity of the rejected froth. As shown in Figure 7, the fiber consistency in the suspension decreased exponentially with increased conductivity, whereas the wet reject increased with the increase of froth conductivity. The data presented in Figure 7 were obtained on three different days of a 2-week period. The consistency of the data indicated the repeatability of the trials and measurements were quite good. The data validated our hypothesis (3): conductivity can be used to monitor fiber and wet reject in froth flotation. The function j (σ_{froth}) in Equation (6) can be approximated by an exponential decay function. Furthermore, the wet reject can be approximated by a logarithmic function of froth conductivity when aeration was varied while keeping surfactant concentration constant at 50 mg/L.

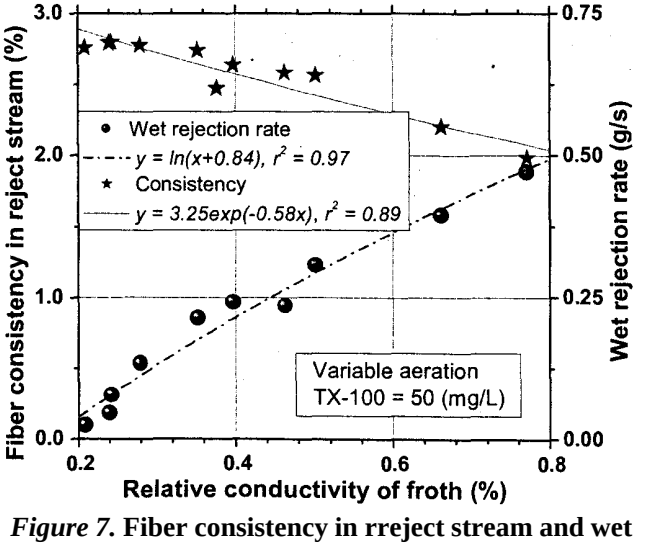

Figure 7. **Fiber consistency in rreject stream and wet rejection rate as a function of the measured relative froth conductivity for varying aeration flow rates.**

Effect of Surfactant

Another set of experiments was conducted to study the effect of surfactant concentration on the determination of fiber consistency and wet reject using conductivity. Air flow rate was fixed at 25 L/min whereas surfactant concentration was varied, with 25, 50, 100, and 200 mg/L in the suspension. We found again that fiber consistency in the reject stream decreases with the increase of the relative conductivity of the froth. For example, function j (σ_{froth}) in Equation (6) is a monotonic function of froth conductivity, whereas wet reject increases with the increase in froth relative conductivity as shown in Figure 8. We did not attempt to fit the fiber consistency and wet reject data sets because of concerns in obtaining good nonlinear fits with only four data points and unknown functionality of the data sets. Different surfactants were also used to evaluate the effect of surfactant on fiber consistency and wet reject using conductivity. As expected, different surfactants affect fiber and wet rejection differently because of the variations in their effect on froth stability. These variations were similar to the surfactant concentration effect on froth stability and therefore fiber rejection.

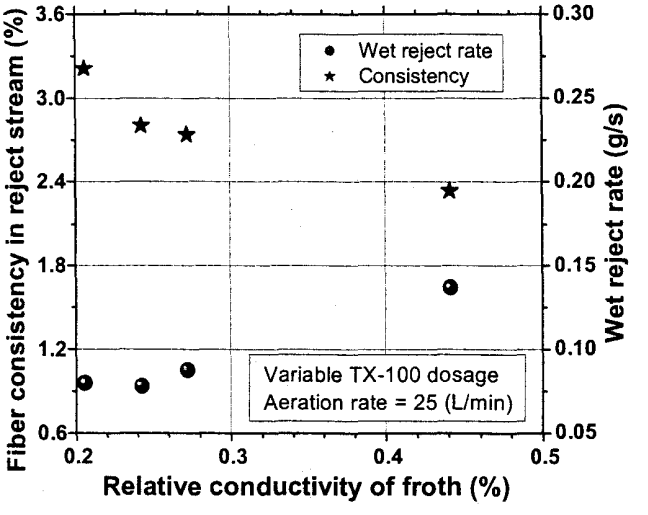

Figure 8. **Fiber consistency in reject stream and wet rejection rate as a function of the measured relative froth conductivity for varying surfactant concentrations.**

Effect of Suspension Fiber Consistency on Fiber Consistency in Reject Stream

Experiments were also conducted with different fiber consistencies in the suspension. Figure 9 shows that increasing fiber consistency in the suspension increases the fiber consistency in the reject stream. From the two suspensions of different fiber consistencies evaluated, we concluded that fiber consistency in the reject stream (the slope of the linear regression lines shown in Figure 9) is linearly proportional to the fiber consistency of the suspension.

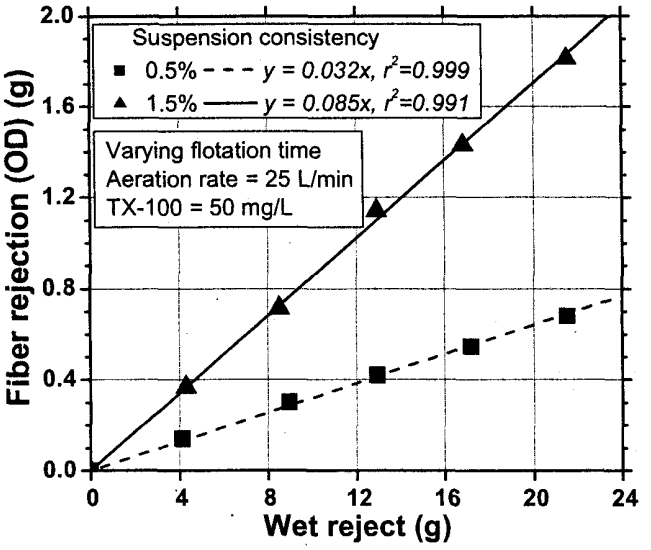

Figure 9. **The effect of fiber consistency in the suspension on the correlation between fiber reject (oven-dried (OD)) and wet reject.**

Hypothesis (3): Froth Conductivity for Flotation Deinking Application–Denver Cell

To demonstrate the applicability of the conductivity technique to monitor wet and fiber (total solid in this case) reject in flotation deinking process, flotation experiments were conducted in a Denver flotation cell. Figure 10 shows that the solid (oven dry, OD) consistency in the reject stream decreases exponentially with the increase of average relative conductivity of the froth. The exponential decay function fits the conductivity data very well with a correlation coefficient of about 0.99, indicating that the function j (σ_{froth}) in Equation (6) can be approximated by an exponential decay

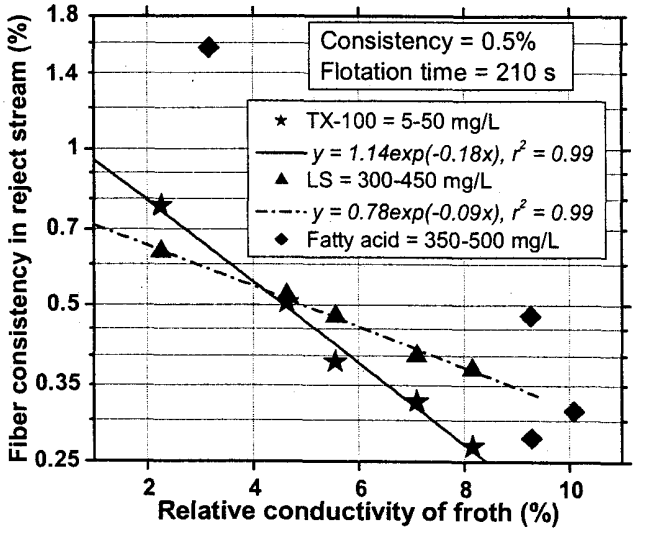

Figure 10. **Fiber consistency in reject stream as a function of the measured relative froth conductivity in flotation deinking using different surfactant and its concentrations in the Denver cell.**

function. Similar results were obtained when different deinking surfactants (fatty acid and Lionsurf 5140) were used (Fig. 10). We found that measured froth conductivity also correlates very well to the total wet reject, as shown in Figure 11. The data from Lionsurf and fatty acid were omitted for clarity. Wet rejection increased with increasing measured conductivity. As a result, the total solid (OD) rejects, (the product of solid consistency in the reject stream and the total wet rejects) can also be determined from the conductivity data. The exponential relation for wet reject (shown as dash-dotted line in Fig. 11) was derived from the experimentally fitted correlations for solid consistency (Fig. 10) and fiber reject (Fig. 11). The predicted wet rejects agree with experimental data very well. The results obtained in Denver cell (Figs. 10 and 11) using wood pulp further validated hypothesis (3) in the Introduction: froth conductivity can be used to monitor fiber and wet reject in flotation deinking operations. Furthermore, the functionalities of Equations (5) and (7) are clearly defined by the experimental data (Fig. 1 1): function $R_{froth}(\sigma_{froth})$ is an exponential function when TX-100 was used in a Denver cell flotation deinking of newsprint paper. As a result, total solid rejection is linearly proportional to the measured average froth conductivity with a correlation coefficient of 0.99.

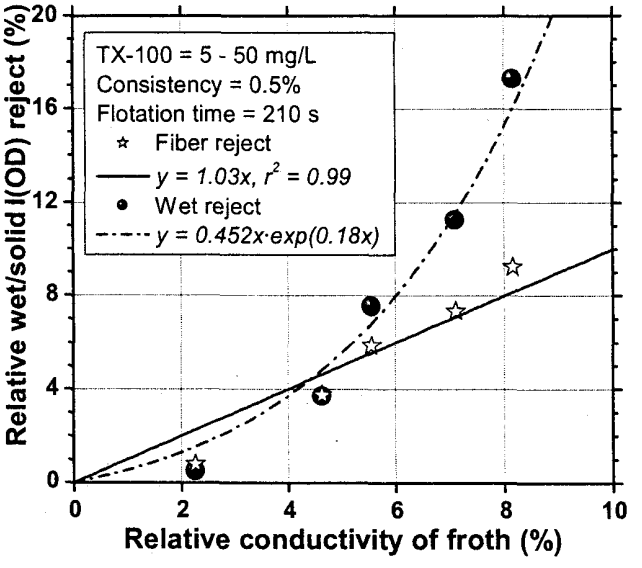

Figure 11. **Total solid (OD) reject and wet reject as a function of the measured relative froth conductivity in flotation deinking under different surfactant concentrations in the Denver cell.**

SUMMARY

Conductivity of froth produced by air flotation of fiber suspension in a column flotation cell was measured using a conductivity probe constructed of platinum wires. We found that the Lemlich relation [9] between the conductivity of froth and liquid volumetric content of a froth is equal to one

third of the liquid volumetric fraction in the froth, and holds even when the froth contains solid materials such as fibers and fillers. Furthermore, froth production or rejection through overflow caused by the variation of each flotation parameter (surfactant concentration or aeration rate) can be uniquely characterized by froth conductivity. Therefore, total liquid/wet rejection, the product of froth volumetric rejection and liquid volumetric fraction in froth, can be monitored by froth conductivity. Fiber consistency in froth also correlates with the measured relative conductivity of the froth under various operating flotation conditions based on froth drainage theory. Moreover, fiber consistency in the froth was found to decrease exponentially with the increase in froth relative conductivity. As a result, fiber (solid) rejection can also be monitored using froth conductivity. The specific functionalities of liquid (wet) and solid (fiber) rejection (Eqs. (5) and (7)) with froth conductivity were experimentally determined for given flotation experiments conducted in this study, validating the concept of the proposed conductivity probe.

The conductivity technique was also applied to laboratory bench-scale flotation deinking experiments. We found that the fiber consistency in the reject stream decreased exponentially with the time-averaged conductivity of the rejection froth, whereas the wet reject rate increased exponentially with the increase in froth conductivity. As a result, the fiber reject increased linearly with the increase in the average froth conductivity. These results demonstrated that a conductivity probe can be used to perform online monitoring fiber (solid) consistency in the reject stream, and fiber (solid), and wet reject in flotation deinking operations.

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