ANALYSIS OF BUBBLE GENERATING DEVICES IN A DEINKING COLUMN

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ABSTRACT

Column flotation as a concept was introduced approximately 90 years ago at Inspiration Copper Co., Arizona, with the first successful installation occurring at Les Mines Gaspe, Quebec, in 1981. Column flotation has since been applied to many other industries including deinking of recycled paper.

The research is a comparison of industrial bubble generating devices in a pilot and laboratory column using water/Dowfroth and pulp sampled on-line from a local deinking plant. The pilot column tested combinations of 6, 4 and 2 stainless steel (ss) porous spargers, and filter cloth and jetting sparger; the lab column used a single ss porous sparger. Long term tests on the pilot column were also done to evaluate maintenance issues.

Trends from the water/Dowfroth tests were used to predict results using pulp. Six ss spargers outperformed the other spargers in all cases. The performance of the lab column sparger matched 4 spargers, with the filter cloth performing marginally better than the jetting sparger or 2 spargers.

Gas holdup (Eg) and bubble surface area flux (Sb) gave good correlation with ink removal with with all spargers falling within a narrow range. Surface area flux is suggested over Eg unless bubble diameter or superficial gas velocity are indeterminable. Sb > 100 s^{-1} gave ink removals equal to the plant Voith cells. An Sb below 40 $s^{-}1$ gave zero ink removal. The lab and pilot column followed slightly different trends which was attributed to column diameter (i.e., wall effects).

The ss and filter cloth spargers present long term maintenance issues due to plugging. The performance of the 6 ss spargers decreased more quickly than any other during the long term tests, attributed to lower air velocities per pore.

RÉSUMÉ

Le concept de flottation en colonne a été introduit il y a approximativement 90 ans à Inspiration Copper Co., en Arizona, la première installation réussie ayant eu lieu à Les Mines Gaspé, Québec, en 1981. La flottation en colonne a depuis été appliquée à plusieurs autres industries incluant celle du désencrage du papier recyclé.

Cette recherche est une comparaison d'appareils générateurs de bulles industriels d'une colonne pilote et d'une colonne de laboratoire, utilisants des systèmes eau/Dowfroth et pulpe échantillonnés en ligne à partir d'une usine de désencrage locale. La colonne pilote a été utilisée afin de tester des combinaisons de 6,4 et 2 générateurs de bulles poreux faits d'acier inoxydable (inox), un filtre de toile, et un générateur de bulles à jets; la colonne de laboratoire n'a utilisé qu'un seul générateur de bulles poreux en inox. Des tests à long terme ont aussi été réalisés sur la colonne pilote afin d'évaluer les problèmes d'entretien.

Les tendances des tests eau/Dowfroth ont été utilisées dans la prédiction des résultats utilisants la pulpe. Les six générateurs de bulles en inox ont surpassé les performances de tous les autres générateurs dans tous les cas. La performance du générateur de la colonne de laboratoire a égalé celle des quatre générateurs; le filtre de toile a performé un peu mieux que le générateur à jets ou deux générateurs.

La fraction gazeuse (Eg) et le flux de surface des bulles (Sb) sont en corrélation étroite avec le désencrage pour tous les générateurs de bulles. Le flux de surface est suggéré au lieu de Eg à moins que le diamètre de bulle ou la vitesse superficielle du gaz soient indéterminables. Sb > 100 s-1 a donné des désencrages équivalents à ceux des cellules Voith de l'usine. Un Sb en-dessous de 40 s-1 n'a donné aucun désencrage. Les colonnes de laboratoire et pilote ont

suivi des tendances quelque peu différentes qui ont été attribuées au diamètre de la colonne (i.e., effets du mur).

Les générateurs en inox et le filtre de toile présentent à long terme des problèmes d'entretien dus au bouchage. La performance des 6 générateurs en inox a diminué plus rapidement que tous les autres durant les tests à long terme, attribué à des vitesses d'air par pore plus basses.

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1. Introduction

1.1 Background

Flotation was first patented as a separation process as early as the mid19th century, but it was not used in an industrial application until 1905 when the Potter-Del-prat process was tested at Broken Hill in Australia [Arbiter, 1985]. The first known use of flotation columns in North America was in 1910 at Inspiration Copper Co. with the testing of porous bottomed columns using carborundum stone or canvas as the air distribution material [Gahl, 1917]. These early flotation column tests met with limited success due to the porous spargers quickly clogging with fines. Seventy years would pass before column flotation would be tested again in a mineral system, with the first permanent installation occurring at Les Mines Gaspé in 1981. The inventors, Boutin and Tremblay, patented the flotation column used at Les Mines Gaspé with the installation credited to the promotional work of Don Wheeler of the Column Flotation Company of Canada Ltd., who was responsible for overcoming some of the initial technical problems. The column was called the Canadian column but due to the widespread use of its basic design has since become known as the conventional column [Finch and Dobby, 1990].

The flotation columns at Les Mines Gaspé were used for molybdenum cleaning and eventually replaced thirteen stages of mechanical flotation cells due to their improved selectivity which gave a higher grade product at the same recovery. The benefits resulted in the use of flotation columns quickly spreading to other molybdenum plants and eventually to other mineral processing plants and industrial processes. Column flotation is now used in areas as diverse as coal cleaning, the oil industry, the food industry, medicine (to separate various organic compounds), and paper recycling.

1.2 Flotation Columns in Deinking

Paper recycling is an industry which has many goals in common with the mineral processing industry. The most important of these is the separation/concentration step in which a valuable product must be separated from an undesirable contaminant, while minimizing losses of product to the waste stream. It is in this particular area that column flotation is most useful due to the nature of its design.

In comparing a mechanical flotation cell to a conventional flotation column the important distinction is the presence of a deep froth zone. It is the froth zone, which when washed gently from above with a wash water stream, will reject a significant amount of entrained material. The successful rejection of entrained material using wash water is dependent on the condition that the flow of liquid entering is greater than that exiting with the reject stream. The ability to reject entrained particles is called cleaning and results in higher grades in the mineral industry or greater fiber yield for the pulp and paper industry. In a paper recycling mill a bank of "mechanical" flotation cells can have losses of 10 to 15% of the feed to the rejects, which is approximately twice the amount of losses in a flotation column [Watson *et al.*, 1996]. The other benefits of conventional flotation columns in comparison to mechanical cells are a smaller footprint due to their vertical orientation, and lower energy requirements since flotation columns do not require agitation.

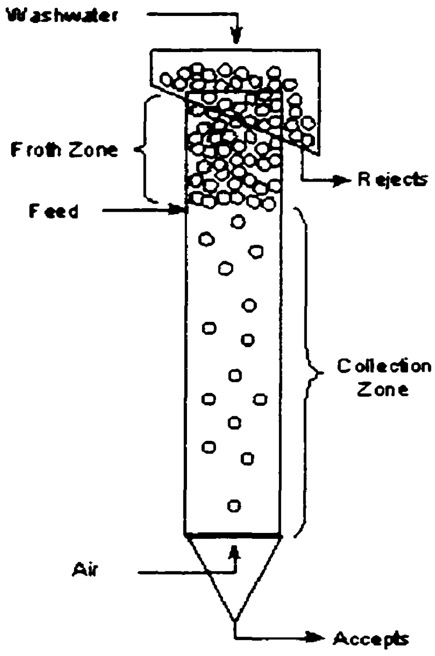

Figure 1-1: Schematic of a flotation column. (Terminology refers to use in the paper deinking industry).

1.3 Bubble Generation: A Problem for Column Flotation

The main concern facing the application of flotation columns today are much the same as in 1910: reliability of the air distributors. This problem is found in both the mineral and paper recycling industry and has driven many innovations (Figure 1-1).

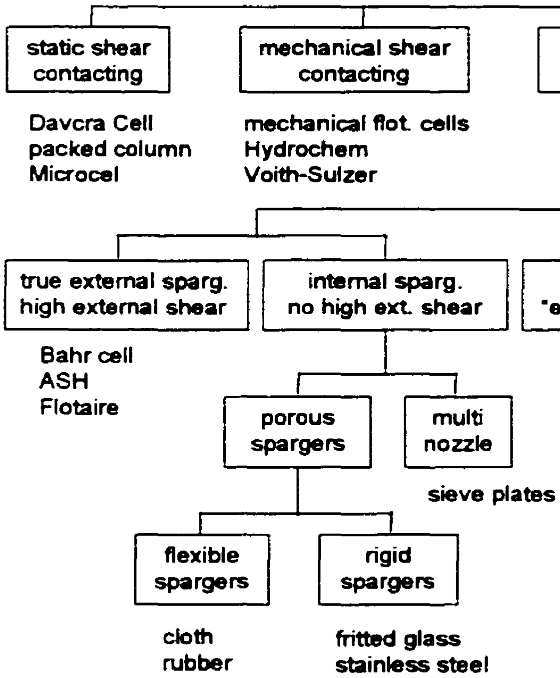

Figure 1-1: Bubble generating techniques (adapted from Paleari, 1993)

The challenge for porous media spargers is to develop a design resistant to plugging of the pores or if the pores are plugged to remove the obstruction easily (eg., using a pulse of air in the case of flexible spargers). Static shear bubble generating devices use turbulence to break an air-slurry stream into finely dispersed bubbles. These devices may wear quickly in abrasive environments such as the mineral industry but due to their design they tend to resist plugging. Jetting bubble generating devices use high relative velocities of air and slurry to induce shear and produce bubbles. The high velocities produced through the single orifice tend to keep the device from plugging. Mechanical shear contacting is used in mechanical cells, the mainstay of the mineral industries. These systems are continually being improved due to external pressures such as lower feed grades, a desire for higher product grades, or the need to minimize fiber loss in the case of the pulp and paper industry.

1.4 Research Objectives

This thesis concerns the application of flotation columns to ink removal from a recycled paper pulp stream. The experiments were performed at the Avenor paper recycling plant located in Gatineau, Qc. which has a 600 tpd capacity using two lines of 6+2 Voith flotation cells (Figure 1-1). The first six cells are used for deinking with the remaining two cells for pulp fiber reclamation from the waste stream. The Voith cells have the same general appearance of a bank of mechanical cells, but use an internal self-aspirating venturi contactor and therefore cannot be considered 'true' mechanical cells.

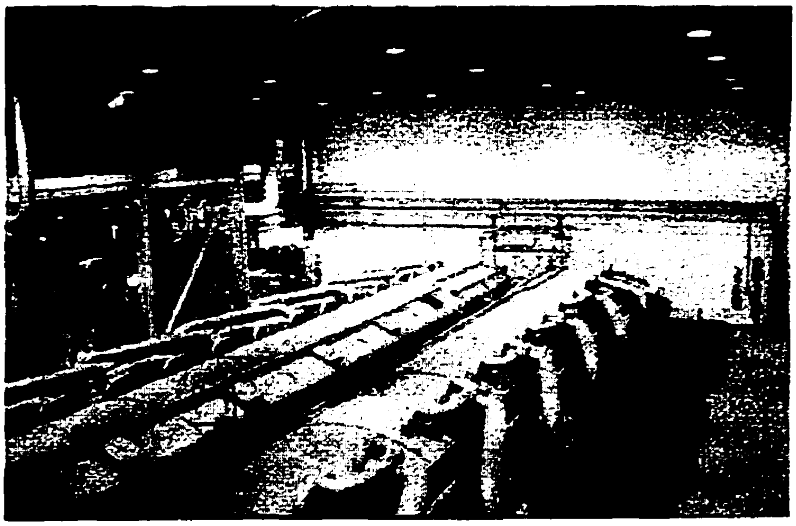

Figure 1-1: Voith cells located at Avenor Pulp Mill in Gatineau, Qc.

The experimental setup at Avenor consists of two columns, a lab scale and pilot scale column. The feed for the tests was diverted either from the feed to or accepts from the Voith cells. The research objectives were as follows:

1. To evaluate the performance of the Voith cells at the Avenor pulp and paper plant in Gatineau, Qc.
2. To compare the deinking performance of a lab scale column to the deinking performance of a pilot scale column to check aspects of the scale-up methodology.
3. To compare the deinking performance of industrial air injection techniques in the pilot scale column using sintered porous stainless steel spargers, filter cloth spargers, and a jetting sparger.

1.5 Thesis Outline

The major sections of the thesis are as follows:

Literature Review

In the literature review the general characteristics of pulp are discussed with a short description of the flotation chemistry requirements for deinking. There is a discussion on the effect of variables on gas holdup. Finally, the drift flux model, a derivation of bubble surface area flux, and flotation kinetics are described.

Experiment

Descriptions of the equipment used in the research are given. Sample preparation and measurements are discussed, and calculations for expressions used in the thesis are given. The experimental design is also presented.

Results/Discussion

The results are presented and discussed following the general outline of the experimental design.

Conclusions

Conclusions are given of the work presented in the results/discussion.

Appendices

The appendices contain the raw data of the work presented in the results/discussion.

2. LITERATURE REVIEW

2.1 Deinking Pulp

Flotation, a vital separation process in many industrial systems, relies on physical and chemical interactions between the particles in the slurry and a dispersed air bubble swarm. Separating a particle from the bulk is dependent on the frequency and size of air bubbles in relation to the size, shape, and number of particles. The surface characteristics of the particle, which can be changed by chemicals called surface active agents or surfactants, affects the interaction with the air bubbles, frequently making the particle hydrophobic so collection can occur.

In a deinking system paper is mixed with water and chemicals in a pulper where shear forces break the mixture into a fibrous pulp. The chemicals (caustic soda, hydrogen peroxide, surfactants, and others) are selected to liberate the ink from the fibers and facilitate the capture of ink onto air bubbles [Ferguson, 1992a, 1992b]. Fatty acid soaps have been the traditional surfactant, acting as both a collector and a frother [Mak and Stevens, 1993]. The term collector refers to the capture of the ink particles onto the surface of the air bubble, which in the deinking system is believed to occur by the formation of microprecipitates of |ink -- fatty acid – calcium ions| linked to a fatty acid coated air bubble (see Figure 2-1) [Putz *et al.*, 1993]. Frothers are surfactants used to aid in the formation and stabilization of small bubbles [Wills, 1992].

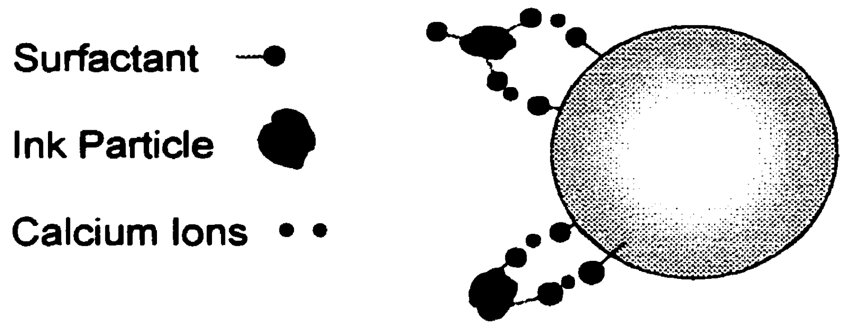

Figure 2-1: Schematic model of air bubble -- particle attachment in a deinking system.

The fibers in the pulp are flexible, elastic asymmetric particles giving pulp a pseudoplastic non-Newtonian behaviour. Pseudoplastic fluids approach the rheology of water as the shear is increased, most likely in this case because of the disintegration of fiber flocs, or as the consistency (solids weight percent of dry fibers) is decreased (Figure 2-2). Fiber flocs are mechanical entanglements of fibers which occur at consistencies as low as 0.5 wt%, with continuous networks of flocs existing at 0.8 wt%. These flocs can affect air bubble movement, increasing bubble coalescence and lowering the gas holdup within the column.

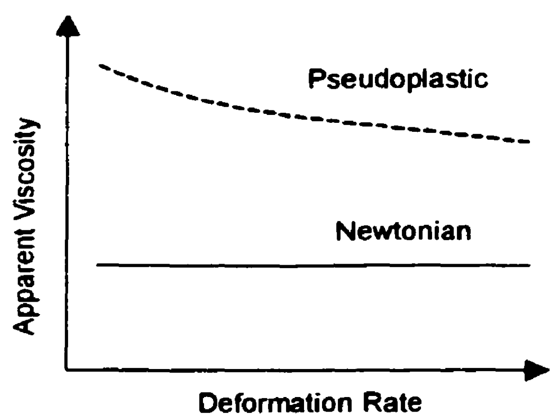

Figure 2-2: Apparent viscosity vs. the deformation rate for one-dimensional flow (adapted from Fox, 1992)

2.2 Gas Holdup

Gas holdup (Eg) is a measurement of the fraction of air present in a fixed volume (see section 3.4.3). Assuming the bubble generating device is constant, Eg changes with superficial gas velocity (Jg), bubble diameter (d_b), pulp consistency and frother concentration (due to its effect on d_b). Normal column operation is in the bubbly flow regime which is a region indicated by quiescent conditions with relatively uniform bubble size (Figure 2-1). Churn turbulent conditions occur when an increase in Jg does not give a corresponding increase in Eg which has been termed the flooding point [Lockett and Kirkpatrick, 1975]. The churn turbulent regime is characterized by large non-spherical bubbles called slugs which are formed due to a combination of high Jg and bubble coalescence from increased liquid and bubble flow. The transition from bubbly flow to churn-turbulent occurs at Jg's from 1 to 4cm/s dependent on the pulp characteristics or frother concentration. Changes in the system as Jg is increased are characterized by loss of interface between the collection zone and froth zone (distinguished by the same Eg in both zones), and loss of positive bias due to an entrainment of water across the froth–collection zone interface that is greater than the flowrate downward from the washwater.

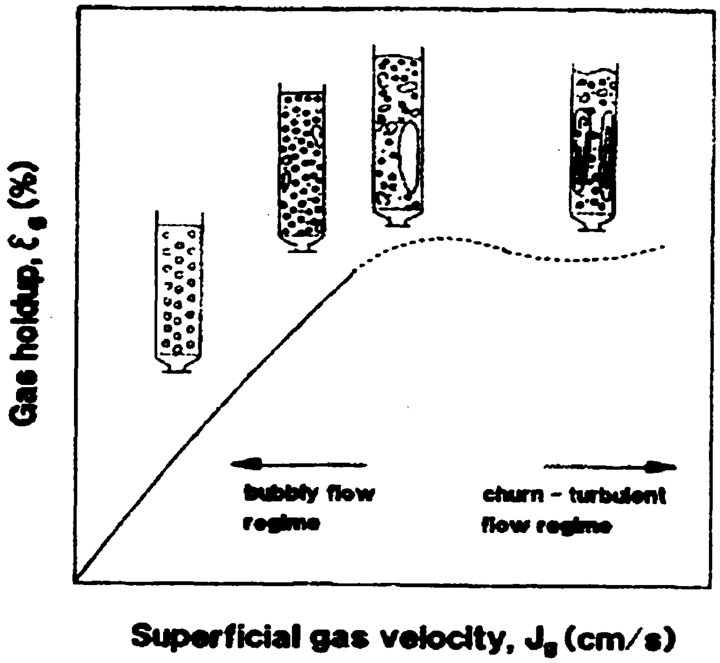

Figure 2-1: Diagram of bubbly flow and churn-turbulent regimes in a flotation column with increasing Jg [Finch and Dobby, 1990]

Eg is inversely proportional to consistency, with increasing consistency giving lower gas holdups (Figure 2-2). In practice deinking flotation is at a consistency of 0.8 to 1.2 wt% to maximize throughput and ink removal [Smook, 1992]. This is an order of magnitude lower than in the mineral industry which normally operates at consistencies in the 30 wt% range. The "apparent" consistency of fibers in water is much greater due to fiber swelling; put in relative terms it is possible to hold pulp in your hand at consistencies of 3 to 4 wt%.

In a water only system Eg increases with the addition of frothers such as Dowfroth 250C up to concentrations of around 15 ppm; concentrations above 15 ppm give relatively little further benefit (Figure 2-3, Figure 2-4).

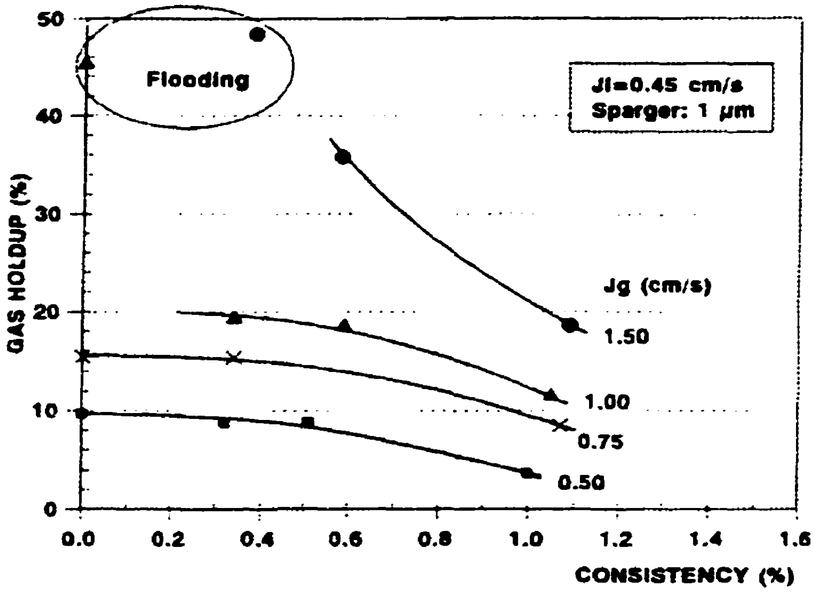

Figure 2-2: Gas holdup versus consistency over a range of Jg typical in a paper pulp system [Janse *et al.*, 1998]

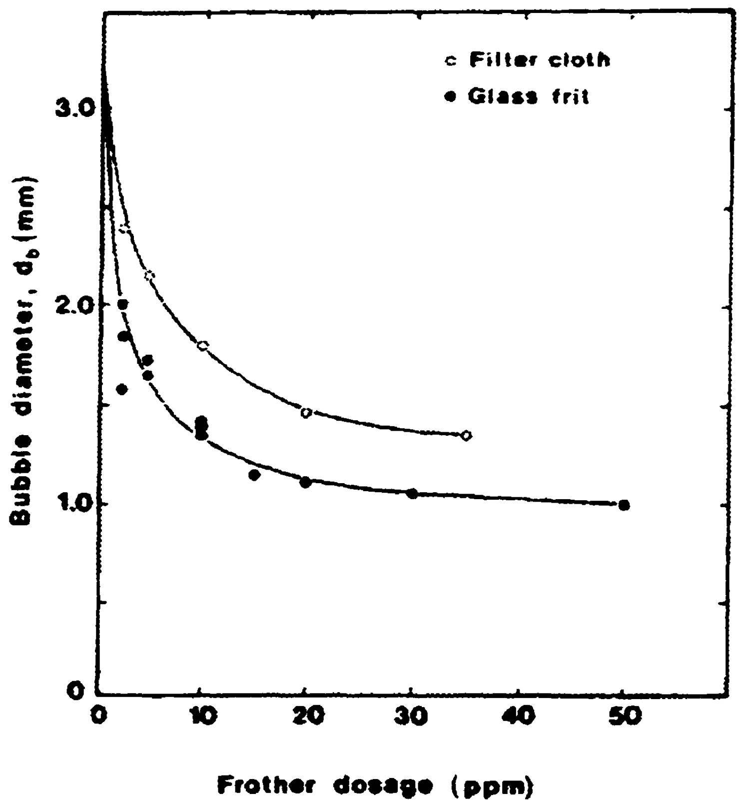

Figure 2-3: Effect of Dowfroth 250C (frother) dosage on bubble diameter, Jg=1.3cm/s [Flint *et al.*, 1988]

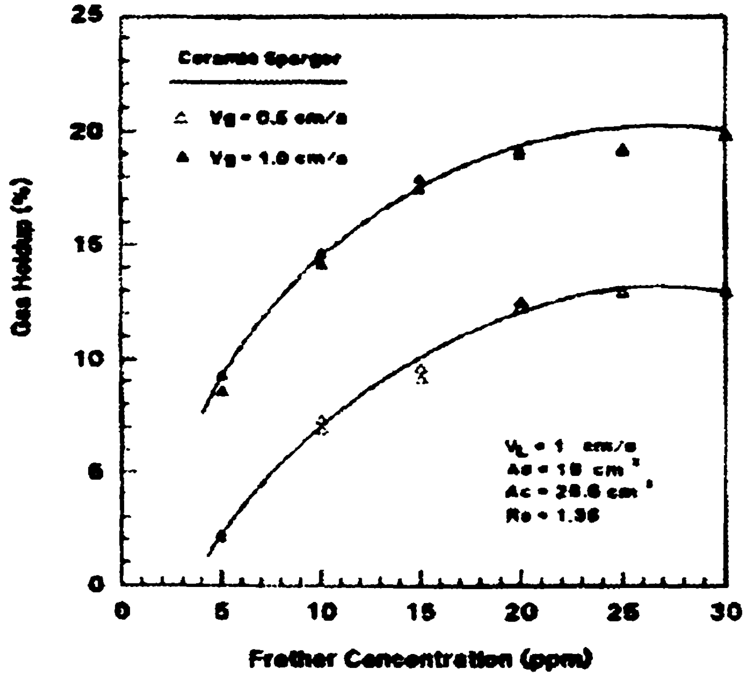

Figure 2-4: Effect of frother concentration (Dowfroth 250C) on gas holdup [Xu and Finch, 1989]

The type and surface area of the bubble generating devices used also has an effect on the bubble diameter [Xu and Finch, 1989]. Introducing R_s, the ratio of the column cross-sectional area to the surface area of the sparger, the following relation relates d_b to R_s and Jg for an $R_s \leq 1$:

$$d_b = C_1[R_s \cdot J_g]^n$$

Equation 1

where C_1 and n are empirical constants. It was found that a reasonable fit was obtained with C_1 of 1 and n equal to 0.25 for a selection of steel, cloth, and perforated rubber bubble generating devices. From Figure 2-5 it is evident that the sparger type had a relatively minor effect on the bubble diameter.

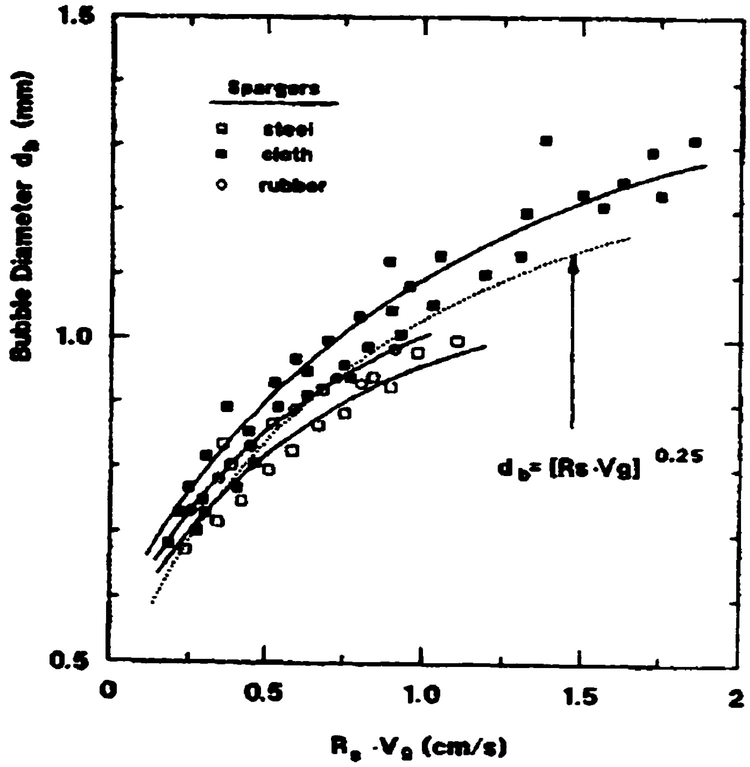

Figure 2-5: Effect on d_b of R_s and superficial gas velocity for steel, cloth, and rubber spargers *[Xu and Finch, 1989]*

2.3 Drift Flux Analysis

From knowledge of Eg, Jg, and the superficial liquid velocity (equal to the accepts from the column in the current situation), $J_{Acc.}$, the bubble diameter can be estimated using drift flux analysis. The concept of drift flux analysis was originally introduced by Wallis [1969] and has been applied to both two phase and three phase systems. For a flotation column operating with counter-current flow the slip velocity, U_s, between the gas and liquid (or pulp) phase is defined as:

$$U_s = \frac{J_g}{E_g} + \frac{J_{Acc.}}{(1-E_g)}$$

Equation 2

where flow upwards is positive. The terminal rise velocity of a bubble, U_t, can be related to U_s using the following equation assuming a Eg no greater than 30% [Shah *et al.*, 1982]:

$$U_t = \frac{U_s}{(1-E_g)^{m-1}}$$

Equation 3

where the value of m has been related to the bubble Reynolds number, Re_b [Richardson and Zaki, 1954]:

$$m = \left(4.45 + 18\frac{d_b}{d_c}\right)\mathrm{Re}_b^{-0.1} \quad 1 < \mathrm{Re}_b < 200$$

Equation 4

$$m = 4.45\ \mathrm{Re}_b^{-0.1} \quad 200 < \mathrm{Re}_b < 500$$

Equation 5

where d_c is the column diameter. The standard equation for the terminal rise velocity of a sphere is:

$$U_t = \left(\frac{4}{3}\frac{g\,\Delta\rho\,d_b}{\rho_f\,C_D}\right)^{1/2}$$

Equation 6

and the drag coefficient, C_D, can be calculated using an approximation proposed by Schiller and Naumann [1933]:

$$C_D = \frac{24}{\mathrm{Re}_b}\left(1+0.15\,\mathrm{Re}_b^{0.687}\right) \quad \mathrm{Re}_b < 800$$

Equation 7

Rearranging Equation 6 and Equation 7 gives:

$$d_b = \left[\frac{18\,\mu_f\,U_t}{g\,\Delta\rho}\left(1+0.15\,\mathrm{Re}_s^{0.687}\right)\right]^{1/2}$$

Equation 8

Using the approximation m=3 in Equation 3 gave good agreement with photographic measurements and results from other researchers (Figure 2-1) [Banisi and Finch, 1994]. All methods had an R^2 of 0.90 or greater, with the results from Yianatos *et al.* matching Dobby *et al.* giving an R^2 of 0.94. This is to be expected since both Yianatos *et al.* and Dobby *et al.* use the same equations with the former making an initial assumption and iterating the calculations on d_b whereas the latter assumes a value and iterates on m. The regression was done using a linear equation with intercept set to zero.

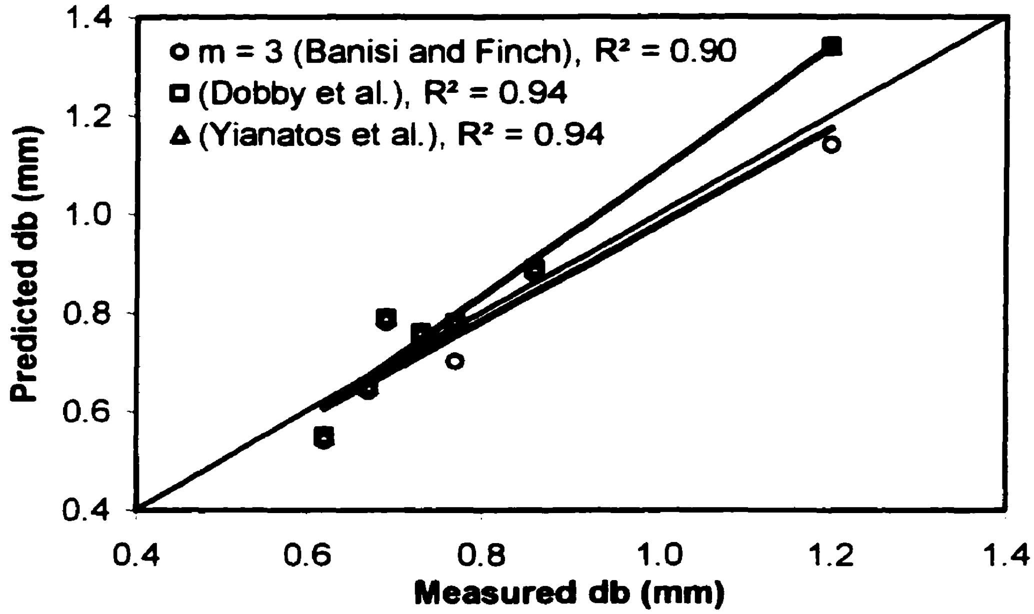

Figure 2-1: Comparison of measured db (photographic) to predicted db for three drift flux calculation methods (data from Banisi and Finch, 1994).

2.4 Bubble Surface Area Flux

Since particles (including ink) are collected through capture onto the surface of an air bubble, it is reasonable that particle removal be related to the total available surface area of bubbles passing through the system per unit time. If we divide by the system (eg. column) cross-sectional area, the term bubble surface area flux is introduced [Finch and Dobby, 1990]. Based on *Figure 2-1*, Equation 9 represents the basic equation,

$$S_b = \frac{n * S}{A_c}$$

Equation 9

where the number of bubbles per unit time is represented by n, S is the surface area of an individual bubble, and A_c is the column cross-sectional area.

Assuming spherical mono-sized bubbles, where d_b is the bubble diameter, and defining n and S as:

$$n = \frac{Q_g}{\frac{\pi}{6} d_b^3} \quad \text{(bubbles/sec)}$$

Equation 10

$$S = \pi d_b^2 \quad (\text{cm}^2/\text{sec})$$

Equation 11

gives Equation 12, which upon substitution and simplification gives,

$$S_b = \frac{6 * J_g}{d_b} \quad (\text{sec}^{-1})$$

Equation 12

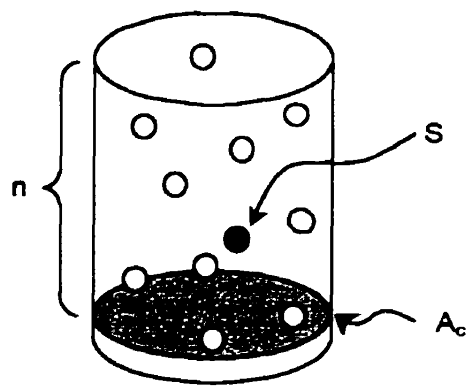

Figure 2-1: Diagram representing concept of bubble surface area flux.

As discussed in section 2.2, there exists particular Jg's that correspond to loss of interface between the collection and froth zones (Jg_{max1}), loss of bubbly flow (Jg_{max2}), and loss of bias (Jg_{max3}). An Sb can be calculated from the maximum Jg to give the corresponding Sb_{max} at a particular d_b (see Figure 2-2).

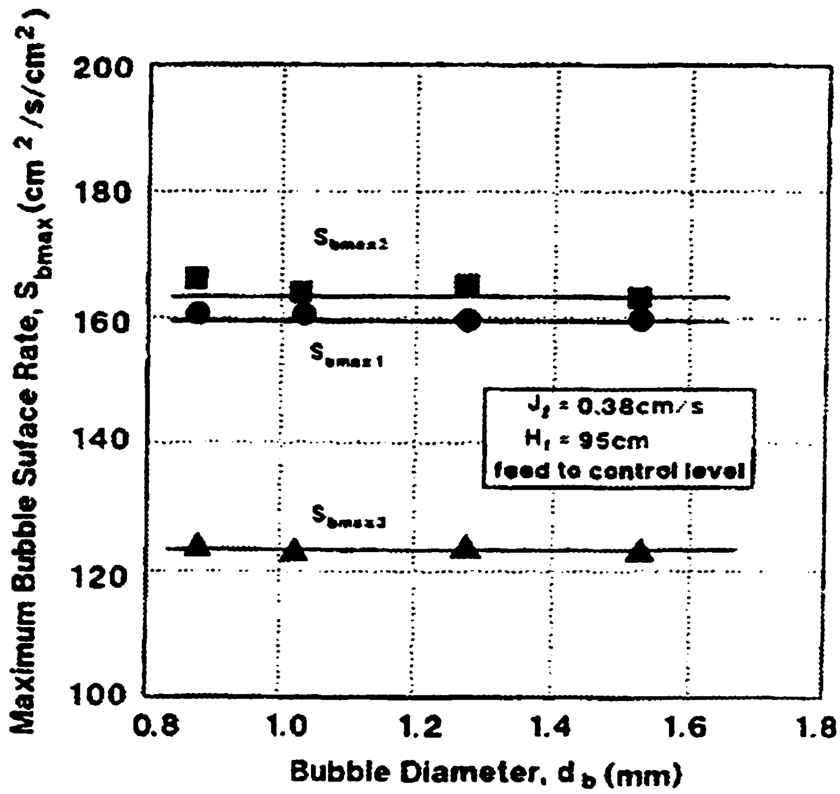

Figure 2-2: Maximum Sb versus d_b for collection zone conditions of loss of interface (S_{bmax1}), loss of bubbly flow (S_{bmax2}), and loss of positive bias (S_{bmax3}) [Xu *et al.*, 1991].

Gorain *et al.* [1997] have related flotation rate constant (k_{fc}) to Sb for shallow froths and found the relationship is linear. The slope depends on factors such as particle size and process chemistry. The deviation from linear was related to froth depth. The k_{fc}-Sb relation was found to be independent of mechanical cell impeller type (Figure 2-3).

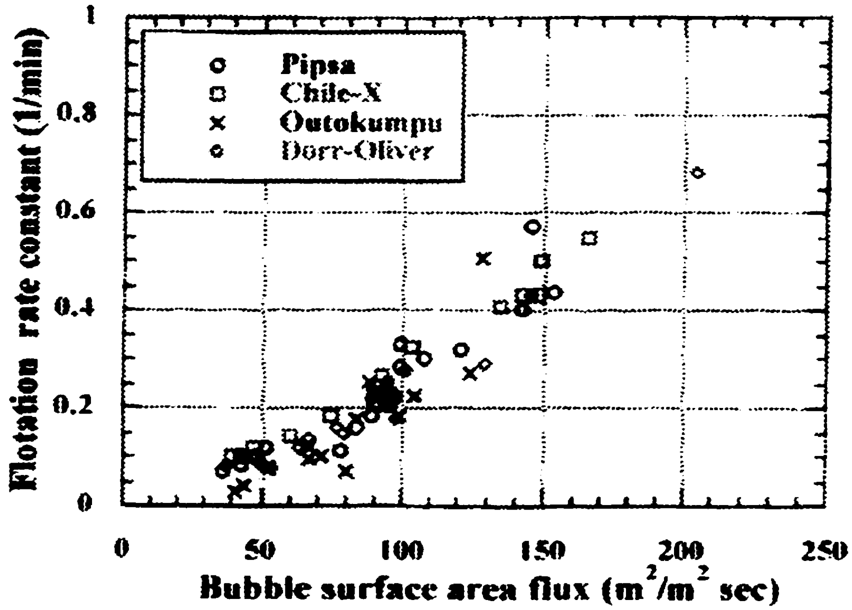

Figure 2-3: Overall flotation rate constant versus Sb for four different impeller configurations on a mechanical float cell operating as a zinc cleaner [Gorain *et al.*, 1997].

2.5 Flotation Kinetics

A flotation column has two distinct zones, the collection and froth zone. If R_f is the froth zone recovery and R_c is the collection zone recovery, then an overall recovery, R_{fc}, can be written as follows (Figure 2-1):

$$R_{fc} = \frac{R_c R_f}{R_c R_f + 1 - R_c}$$

Equation 13

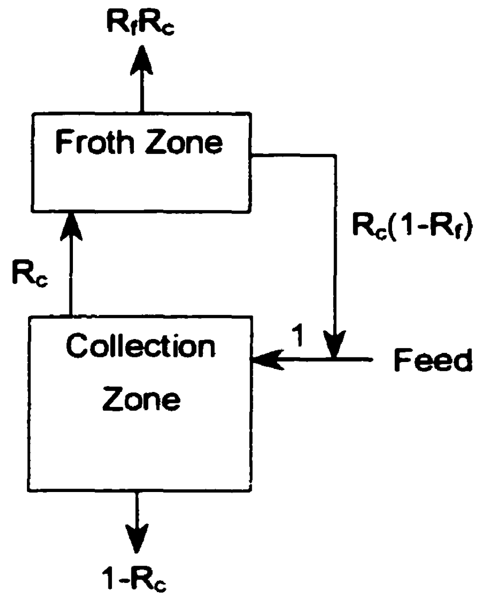

Figure 2-1: **Schematic of froth and collection zone recovery in a flotation column [Finch and Dobby, 1990].**

The collection efficiency of a flotation column is dependent on the action of three probabilities: bubble-particle collision (E_c), attachment of the particle to the bubble (E_a), and particle detachment from the bubble (E_d). These are combined to give an overall collection efficiency, E_k, where E_d can be neglected for quiescent systems such as flotation columns, operating with particles less than critical size [Finch and Dobby, 1990]:

$$E_k = E_c E_a$$

Equation 14

Given E_k it is possible to relate the flotation rate constant for the collection zone to Sb, assuming that E_k is not affected by particle concentration in the collection zone:

$$k_c = \frac{1.5\, J_g\, E_k}{d_b} = \frac{S_b\, E_k}{4}$$

Equation 15

Equation 15 was derived from performing a mass balance on the rate of particle removal as a function of the number of bubbles and the rate of particles removed per bubble.

Assuming that the flotation column follows a first order rate process and is well mixed, R_{fc} can be related to an overall rate constant, k_{fc}, which is a good approximation for columns with a small H_c/d_c ratio:

$$R_{fc} = 1-(1+k_{fc}\tau_p)^{-1}$$

Equation 16

where τ_p is the mean particle residence time in the froth and collection zones. Equation 16 can be rewritten in terms of R_c and k_c to give:

$$R_c = 1-(1+k_c\tau_p)^{-1}$$

Equation 17

where τ_p in this instance is the mean particle residence time in the collection zone. The term k_{fc} can be related to k_c by substituting Equation 16 and Equation 17 into Equation 15 and canceling terms to give:

$$k_{fc} = k_c R_f$$

Equation 18

When collection zone conditions are plug flow, as approached with large H_c/d_c ratios, the overall recovery is as follows:

$$R_{fc} = 1-\exp(-k_{fc}t_p)$$

Equation 19

where t_p is the particle residence time of the froth and collection zone. Substituting collection zone terms for the overall recovery and rate constant and using Equation 15 as before gives the following relation between k_{fc} and k_c for the plug flow case:

$$k_{fc} = \frac{1}{t_p} \ln[\exp(k_c t_p) R_f + 1 - R_f]$$

Equation 20

where the k_{fc} is not a true rate constant as it is a function of t_p [Finch and Dobby, 1990].

3. Experimental Part

3.1 Equipment

The primary equipment used in the research consisted of two flotation columns: a lab column constructed of clear acrylic plastic with an inner diameter of 10 cm and an adjustable height up to 4.7 m, and a pilot column constructed of modular PVC sections with an inner diameter of 50 cm and a height up to 5.1 m (Figure 3-1).

Figure 3-1: Pilot and lab scale columns

The peripheral equipment used for control and data collection consisted of mass air flowmeters, magnetic liquid flowmeters, pressure transducers, and variable speed peristaltic pumps or centrifugal pumps with control valves. The air flowmeters were mass flowmeters manufactured by MKS Inc. with the lab column air flowmeter having a maximum flowrate of 30 litre/min and the pilot column having a maximum flowrate of 400 litre/min. The air supplied to the air flowmeters was from the plant and regulated to a pressure of 80 psig. Each column was also equipped with magnetic flowmeters from Fischer and Porter. The lab column had magnetic flowmeters for the feed and accepts streams with a range setting of 0 to 30 litre/min. The pilot column had flowmeters for the feed, accepts and washwater streams with ranges of 0 to 300 litre/min for feed and accepts and 0 to 30 litre/min for the washwater. The flowmeter for the washwater stream on the pilot column was not used for all the tests; those tests not using the washwater flowmeter are noted in the appendices. Both columns had three Bailey pressure transmitters for level control and gas holdup measurement. The pumps for the lab column were peristaltic variable control pumps by Masterflex for the feed, accepts, and washwater. The pilot column used two Goulds centrifugal pumps for the feed and accepts, and flowrates were controlled with DeZuric control valves. The washwater flowrate to the pilot column was controlled using a hand valve. The washwater for both columns was the recycled process water used as launder water in the Voith cells

All the peripheral equipment was attached to an OPTO1 serial I/O board manufactured by Transduction. The board digitized the 4-20 mA analog signal which was then transmitted to a Pentium 200MHz computer. The software used for data collection and control was FIX DMACS 32-bit by Intellution. The data routinely collected by the software was from the pressure transducers (P1, P2, and P3), the air flowrate, and the feed and accepts flowrates. The washwater flowrate was also collected by computer when possible, otherwise measurements were done using a stop watch and 2.0 litre graduated cylinder. Other measurements not routinely automated were temperature and pH which were measured periodically (and simultaneously) with a Yokohama pH meter equipped with a temperature readout.

The bubble generating devices used in the research were a jetting sparger and two porous spargers, one flexible made of filter cloth and one rigid of sintered stainless steel powder (Figure 3-3). The laboratory column was tested with only a stainless steel porous sparger which was operated in a horizontal position. Up to six stainless steel spargers were used in the pilot column with the sparger ports orientated horizontally and 90° to one another in two sets of three ports (Figure 3-2).

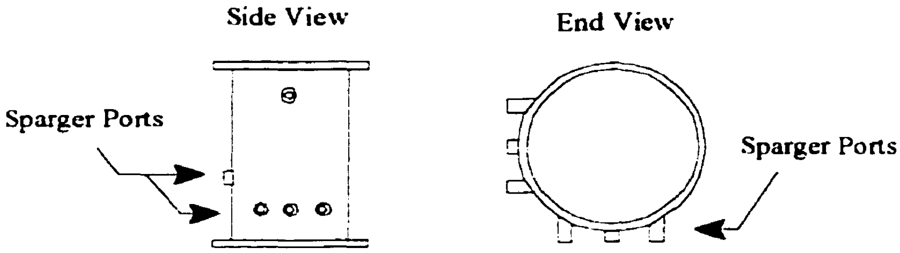

Figure 3-2: Schematic of sparger configuration at the bottom of the pilot column.

The jetting sparger was oriented horizontally and produced bubbles by passing high velocity air between an annular gap at the tip of the sparger directly into the pulp. The filter cloth spargers were hollow plastic cylinders with punched holes covered in felt and up to 5 were arranged in a cross pattern with a vertical orientation. Dimensions and characteristics of the bubble generating devices are in *Table 3-1*.

Table 3-1: Characteristics of bubble generating devices

Column	Sparger	Pore Size (μm)	Length (cm)	Diameter (cm)
Lab	*SS*	*0.5*	*6.2*	*2.2*
Pilot	*#1-5 SS*	*0.5*	*28*	*2.1*
	#6 SS	*0.5*	*43*	*2.1*
	Filter Cloth	*n/a*	*11*	*10*
	Jetting	*n/a*	*30*	*2.1*

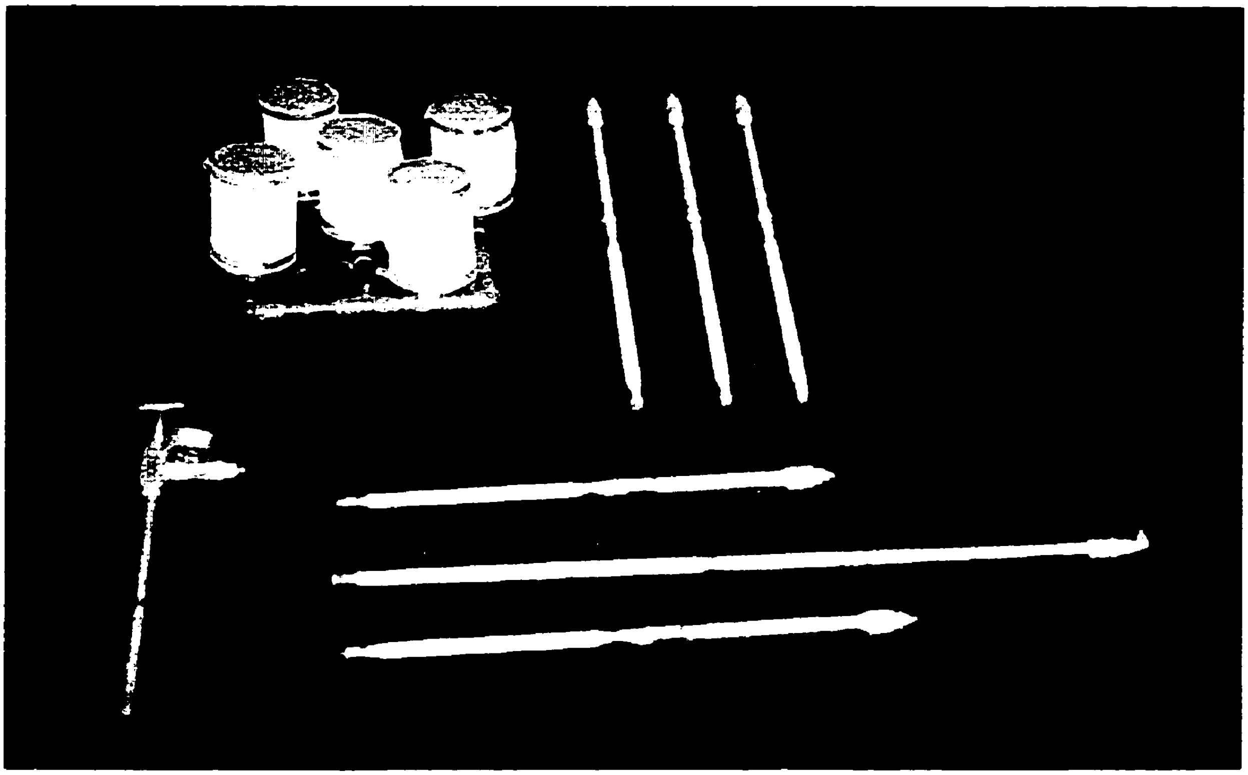

Figure 3-3: Jetting, filter cloth and stainless steel spargers (l to r)

3.2 Measurements

3.2.1 Ink Concentration

The performance of the column was evaluated by comparing the ink concentration present in the accepts with that in the feed. To measure the ink concentration a 15cm circular paper pad was made using the following procedure:

1. An appropriately large sample of the stream was taken (approximately ½ to ¾ liter)
2. The sample was thoroughly mixed prior to filtering with Ahlstrom Filter paper (617 grade, 15 cm diameter, very fast filtration speed)

in a Buchner funnel. The volume of sample filtered was sufficiently large to have a final dry pad weight of approximately 4.0 g.

3. The filter paper was removed and the sample pressed between two blotter sheets using a mechanical roll press and then placed on a conventional fan for room temperature forced air drying.

The ink concentration of a dried pad was measured using a Technidyne Micro TB-1C which gives the concentration in terms of estimated residual ink concentration (ERIC) with units of ppm. The instrument measures the reflectance of the pads at a wavelength of 950nm which is converted into an ink concentration [Jordan and Popson, 1994]. Once the ink concentration of the pads was measured, a flotation efficiency was calculated. The equation is:

$$E = \frac{\left([INK]_{FEED} - [INK]_{ACCEPTS}\right)}{[INK]_{FEED}}$$

Equation 21

where *[INK]* is the concentration of ink in ppm in the feed or accepts streams. An alternate equation developed at the Pulp and Paper Research Institute of Canada (PAPRICAN) proposed a flotation efficiency equation that takes into account the amount of free, floatable ink present versus attached, unfloatable ink [Dorris, 1997]:

$$E_f = 1 - \frac{\left([INK]^{TOP}_{ACCEPTS} - [INK]^{BOTTOM}_{ACCEPTS}\right)}{\left([INK]^{TOP}_{FEED} - [INK]^{BOTTOM}_{FEED}\right)}$$

Equation 22

where ^{TOP} and ^{BOTTOM} refer to the top and bottom of the sample pads of the respective streams. The property exploited is the migration of free ink during filtering. This gives one side of a pad a greater concentration of ink than the other, which is readily seen in the feed stream pad due to the high concentration of free ink. Unfortunately, according to PAPRICAN, this technique is best applied to 1.2g handsheets since 4.0g pads did not show any systematic trend between the amount of free ink and pad sidedness. Therefore, Equation 21 was used to calculate the flotation efficiency for the Voith cells and flotation column. A ratio of the column and Voith cells flotation efficiencies was calculated to reduce process noise. Dependent on the Voith cells removing all of the free ink, the ratio can also take into account the fraction of attached ink.

3.2.2 Consistency

Consistency (which is the dry weight percent solids) was measured using the sample remaining from pad formation as follows:

1. 250 ml of sample was accurately measured.
2. The sample was poured into a Buchner funnel and filtered using preweighed Ahlstrom filter paper (617 grade, 15 cm diameter, very fast filtration speed).
3. The pad and filter paper were removed from the funnel and any remaining fibers were collected on the inside of the funnel.
4. The pad and filter paper were placed in an oven at approximately 150°C until dry.
5. After drying, the pad and filter paper were weighed on an electronic scale. The consistency calculation was as follows:

$$Consistency(\%) = Dry\,Weight\,Pad * \frac{\rho}{250ml} * 100$$

Equation 23

where ρ is the density of the sample (assumed to be that of water) and the dry weight pad was the weight of the pad less the weight of the filter paper.

The only variation in the procedure was for samples too foamy to accurately measure the volume, as was found with many samples from the rejects stream. The weight of a 250 ml sample was measured using an electronic balance and the consistency was then calculated as a ratio of the dry weight of pad (less the filter paper) divided by the weight of sample. Consistency measurements are taken for two reasons: to ensure that tests were performed at constant consistency and to perform a mass balance for fiber loss calculations.

3.3 Procedure

The experiments were divided into three sections: 1) test the ultimate performance of the Voith cells with the lab scale flotation column at a fixed Jg and variable residence time, 2) test the bubble generation devices under batch conditions with water and 30ppm Dowfroth, and 3) test the bubble generating devices using pulp sampled from Voith cell feed while varying residence time and Jg. Consistency was maintained at *ca.* 1.0 ± 0.2 wt.% and the froth depth was 65cm and controlled using a computer PID loop which manipulated the feed flowrate. The following table gives a summary of the experimental design with the order of experiments within each set randomized to minimize systematic error.

Table 3-1: Experimental design for the laboratory and pilot column using pulp feed

Column	Sparger	τ (min)	J_g (cm/s)
Lab	*SS*	*3, 4, 6*	*1.5, 2.0, 2.5*
Pilot	*2 SS*	*3, 6, 10*	*1.5, 2.0, 2.5*
	4 SS	*3, 6, 10*	*1.5, 2.0, 2.5*
	6 SS	*3, 6, 10*	*1.5, 2.0, 2.5*
	Filter Cloth	*3, 6, 10*	*2.0, 2.5, 3.0*
	Jetting	*3, 6, 10*	*2.0, 2.5, 3.0*

The stainless steel and filter cloth spargers were conditioned for one hour before sample collection began to allow the spargers to 'stabilize'. The test then lasted another hour with three samples taken (time zero, the ½ hour and the end). The porous spargers were cleaned before the next test commenced.

The feed and accepts streams were sampled for both the column and Voith cells, and the rejects stream from the column was sampled at the beginning and end of the test. Consistency measurements were done on all the samples taken. Temperature and pH were measured for most of the tests during the last sampling. For those tests where a temperature reading was not taken an average was used from all of the tests. This should not constitute a large error as the range of temperatures is normally between 45 and 50°C. Washwater flowrate was measured at the end of the test using a 2.0 litre graduated cylinder, if it was not done automatically with a magnetic flowmeter. An average of two measurements was used for the washwater flowrate.

For the long term tests in the pilot column the same procedure was used as described for the first hour of sampling. Samples were taken after the first hour from all column streams, and the feed and accepts streams from the Voith cells.

3.4 Calculations

3.4.1 Froth Depth (or Level) Control

The froth depth (or level) in the column was controlled with a computer based PID loop. The error between the level set point (65 cm for all tests) and the interface between the collection and froth zone was calculated by using information from the pressure transducers. Two methods of calculation are possible, using either two or three pressure transducers. The following equation uses two pressure transducers:

$$LEV2 = \frac{h_2\left(\frac{P_3 - P_2}{h_3 - h_2}\right) - P_2}{\frac{P_3 - P_2}{h_3 - h_2} - \rho_f}$$

Equation 24

where the heights, h_2 and h_3, are measured from the launder lip to the middle pressure transducer (2) and to the lowest pressure transducer (3), respectively (Figure 3-1); and ρ_f is an estimation of the froth zone density. The calculation using three pressure transducers is as follows:

$$LEV3 = \frac{h_2\left(\frac{P_3 - P_2}{h_3 - h_2}\right) - P_2}{\frac{P_3 - P_2}{h_3 - h_2} - \frac{P_1}{h_1}}$$

Equation 25

In Equation 25 the froth density is measured by pressure P_1 at distance h_1 from the lip of the column. LEV3 is used if P_1 is above the interface, otherwise LEV2 is used. LEV3 is more accurate than LEV2 which requires the assumption of the froth zone pressure [Gomez *et al.*, 1997].

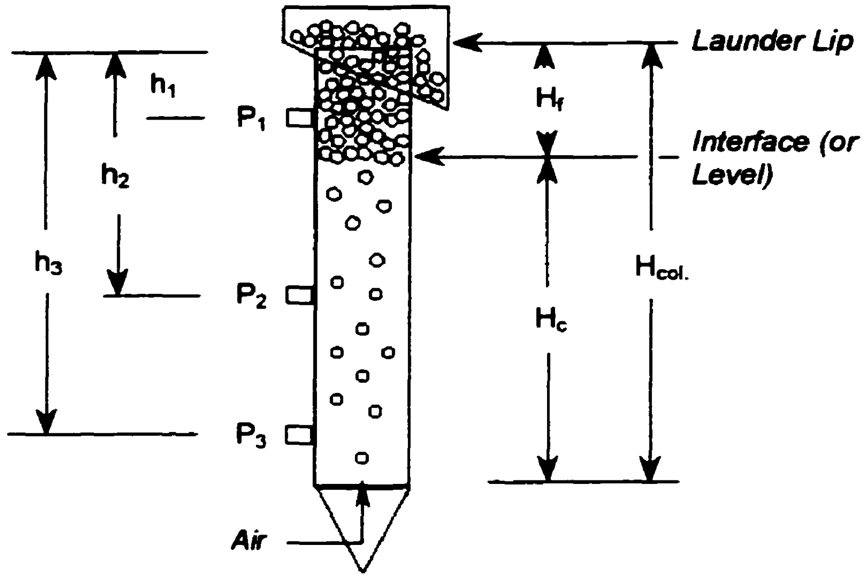

Figure 3-1: Diagram of relative heights of the pressure transducers (P_1 to P_3) and the interface between the froth and collection zone.

3.4.2 Superficial velocity

Superficial velocities are commonly used for flowrates in a flotation column or bubble columns in general. For a volumetric flowrate Q_i into a column of cross-sectional area A_c the calculation is as follows:

$$J_i = \frac{Q_i}{A_c}$$

Equation 26

where the subscripted symbol, *i*, can be *g, acc, ww* or *feed* for superficial gas, accepts, washwater or feed velocity, respectively.

Air flowrate measured by the MKS flowmeter was referenced to 1atm and 0°C. It was adjusted to temperature and pressure conditions inside the column at half the distance between P_3 and P_2 as follows:

$$J_g(P) = J_g(ref) * \frac{T(P)}{T(ref)} * \frac{P(ref)}{[(P_A + P_B)/2 + P(ref)]}$$

Equation 27

where P_3 and P_2 corresponded to pressures in the collection zone, and T(P) was the temperature within the column. P(ref) and T(ref) was one atmosphere and 273K (0°C).

3.4.3 Gas Holdup

Gas holdup (Eg) is the gas fraction in a known volume of a dispersion of gas and liquid (or slurry). It is commonly measured using a pressure difference either from liquid manometers or pressure transducers.

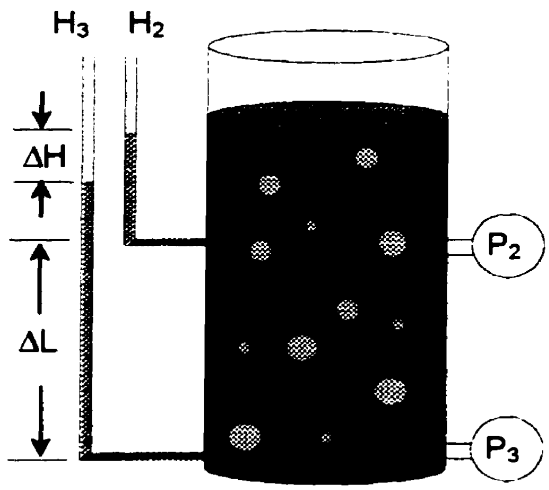

Figure 3-1: Schematic of gas holdup measurement

The equation is as follows:

$$E_g = \frac{\Delta H}{\Delta L} = 1 - \frac{\Delta P}{\rho g \Delta L}$$

Equation 28

where ΔH is difference in manometer heights, ΔP is the pressure difference, ΔL is the distance between the pressure transducers P_3 and P_2, ρ is the density of the liquid, and g is the gravity constant.

3.4.4 Residence Time

The mean residence time was calculated using the volume of the collection zone occupied by the liquid divided by the accepts flowrate:

$$\tau = \frac{(1 - E_g)(H_{col.} - H_f)}{J_{acc}}$$

Equation 29

where the term $(H_{col.} - H_f)$ is the collection zone height (see Figure 3-1) and $(1-E_g)$ accounted for the air/liquid fraction.

3.4.5 Bubble surface area flux and bubble diameter

Bubble surface area flux is the amount of bubble surface area passing through a given column cross-sectional area per unit time. It has units of $(cm^2/s/cm^2)$ or s^{-1} and is calculated using Equation 30 (for a derivation see section 2.4)

$$S_b = \frac{6 * J_g}{d_b}$$

Equation 30

The bubble surface area flux was corrected to a standard temperature of 25°C and pressure of 1 atmosphere using Equation 27 and Equation 31:

$$d_b(atm) = d_b(P) * \left(\frac{P}{P_{atm}}\right)^{1/3}$$

Equation 31

where the bubble diameter was corrected to atmospheric pressure using pressure P (which was an average of P_3 and P_2). The bubble diameter was calculated using the drift flux model (see section 2.3), which gives an average d_b with the assumption that all of the bubbles are spherical, mono-sized, and move with the same velocity. Equipment for sampling d_b was unavailable and a photographic survey would have been impractical because the pilot column was constructed from nontransparent PVC.

4. RESULTS/DISCUSSION

4.1 Evaluation of Voith Cells

As described in section 3.2.1, flotation efficiency is the amount of ink removed relative to ink in the feed, with the maximum efficiency dependent on the amount of free ink. To determine if the Voith cells were operating at maximum efficiency the accepts were tested in the laboratory column. The column residence time was increased to give a flotation efficiency curve that would approach the maximum efficiency. Superficial gas velocity, froth depth, and J_{ww} were kept constant at 1.5 cm/s, 60 cm, and 0.23 cm/s, respectively.

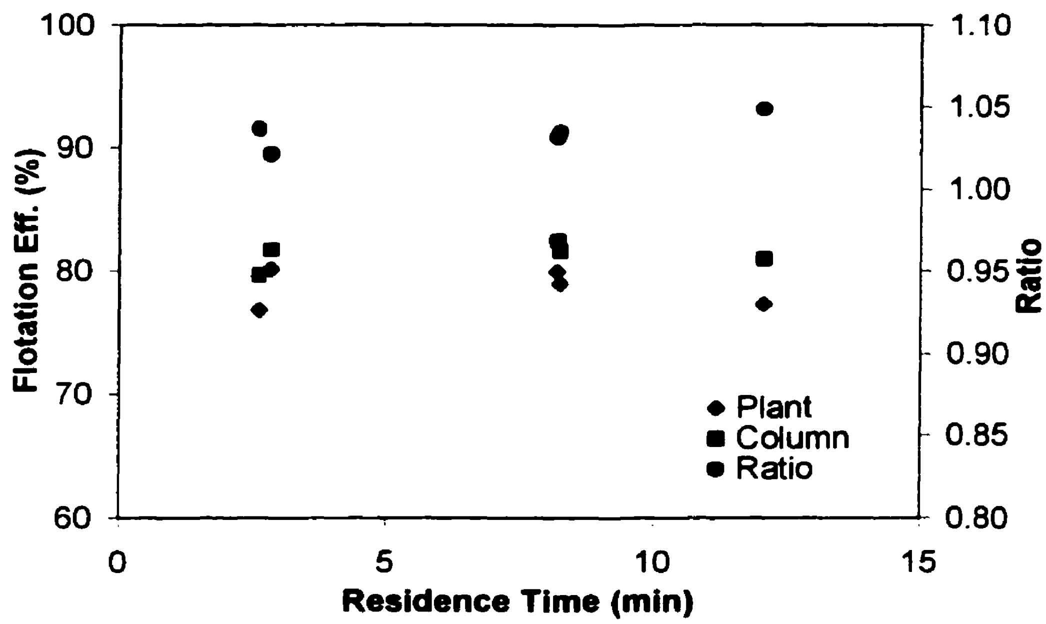

Figure 4-1: Flotation efficiency of lab column using accepts from Voith cells as feed.

The results (Figure 4-1) indicated that the flotation efficiency of the column did not increase with increasing residence time, suggesting residence time did not have an effect. (The residence time of the Voith cells was not changed and the data shown on the graph is to give an indication of the plant flotation efficiency at the time of testing). The average maximum efficiency of the column and plant was 81.3% with an absolute standard deviation (abs. stdev.) of 1.1%. The plant flotation efficiency over the same period was 78.6% (abs. stdev., 1.5%). This suggests the flotation column is able to improve flotation efficiency on average by 3% (abs. stdev., 1.8%). However, a comparison of the means and standard deviations suggests the difference is not significant, and therefore the Voith cells were operating near the maximum flotation efficiency during the testing period.

The results also indicated variations in plant performance corresponded to equivalent changes in column performance (independent of experimental conditions). Therefore, the offset between the plant and column data could be used to show a trend if the lower plant performance was due to ink liberation or chemistry and not changes in plant operating conditions. The adjustable hydrodynamic variable in the Voith cells is the residence time estimated to be between 15 and 20 minutes. Since the plant operates at approximately constant tonnages residence time could be assumed constant. Gas flowrate to the Voith cells is through a self-aspirating venturi orifice and is a function of the pulp flowrate. Since the cells do not have variable speed pumps, gas flowrate can be assumed constant.

A ratio between column and plant data was used to analyze the data. A linear fit to the ratio (Figure 4-1), hence forth called flotation performance or simply performance, had a positive slope of 0.0018, indicating a negligible increase in flotation efficiency with increasing residence time. Noise reduction from the use of flotation performance rather than the raw flotation efficiency is evident when comparing the repeats at the residence times of 3 and 8 minutes. Using an F-test to compare the population standard deviation between two sets, and assuming residence time had no effect on column flotation efficiency (allowing data at 3 and 8 minutes to be combined), indicated that the population standard deviation of the ratio was different from the column at a significance level of 90% (see Appendix). Given the relative standard deviation of the ratio was 0.8% for the combined data, compared to the column which had a relative standard deviation of 1.9%, it is concluded that the ratio reduced the noise in the data.

4.2 Batch Tests in Laboratory and Pilot Columns

The bubble generating devices were first tested under batch conditions using water with 30 ppm Dowfroth as frother. These experiments were intended to indicate the relative performance between devices and therefore the performance that could be expected during testing with pulp. The tests performed in the pilot column were done using Jg's selected so that overflow did not occur. The range of Jg was from 0.3 to 3.3 cm/s giving gas holdups from 2.5 to 25.5%. The results from the ss spargers for the pilot column indicated that 4 ss spargers gave better gas holdups than 6 ss spargers and significantly outperformed 2 ss spargers (Figure 4-1). The lab column gave gas holdups intermediate to the 2 ss spargers and 4 or 6 spargers in the pilot column.

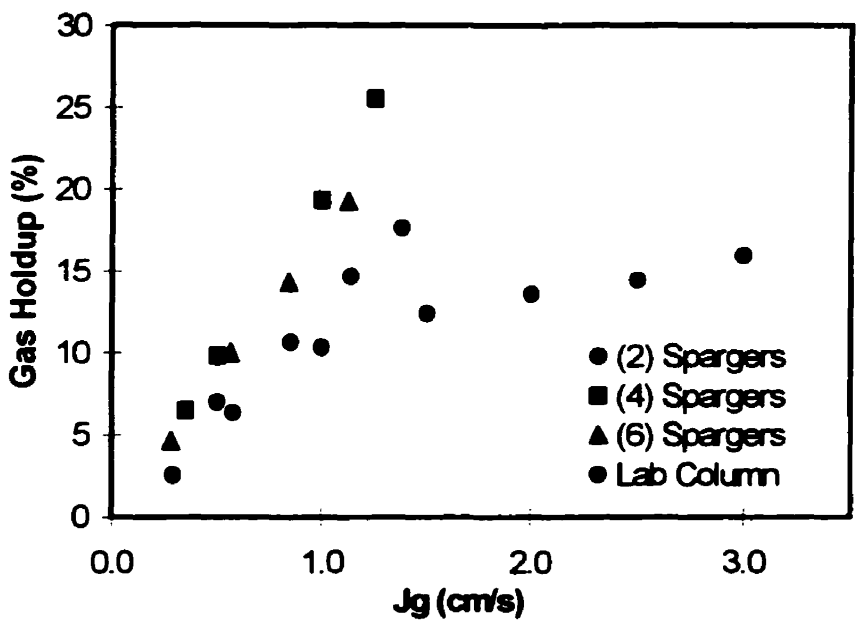

Figure 4-1: Gas holdup versus Jg for ss spargers in batch conditions using water and 30 ppm Dowfroth

The data was replotted using Jg·R_s on the x-axis where R_s is a ratio of the column cross-sectional area and the sparger surface area (Figure 4-2). This is equivalent to volumetric gas rate per unit surface area of sparger (see section 2.2). The motivation was to try to account for the relative sparger surface area and column diameter. Figure 4-2 shows that 6 spargers gave a higher gas holdup than 4 or 2 spargers at equivalent $Jg{\cdot}R_s$. The results for the 4 spargers gave a trend equivalent to the lab column sparger in Figure 4-2. It was felt that R_s should be included whenever possible as it gives a more accurate comparison when using data collected from columns with different and sparger surface area. The R_s values used for the stainless steel and filter cloth spargers are shown in Table 4-1. Note that the sparger surface area for the ss spargers was not simply a multiple of one another, since an effective sparger length was used instead of the geometrical length [Escudero, 1998]. The effective length is the length of the sparger "effectively" used in the formation of bubbles, whereas the geometrical length is measured from a visual inspection of the length of the porous section on the sparger. The geometrical length for all but sparger #6 was 28 cm, whereas the effective length varied from 22.5 to 25.0 cm; sparger #6 had an effective length of 43 cm and was only used in the 6 sparger configuration.

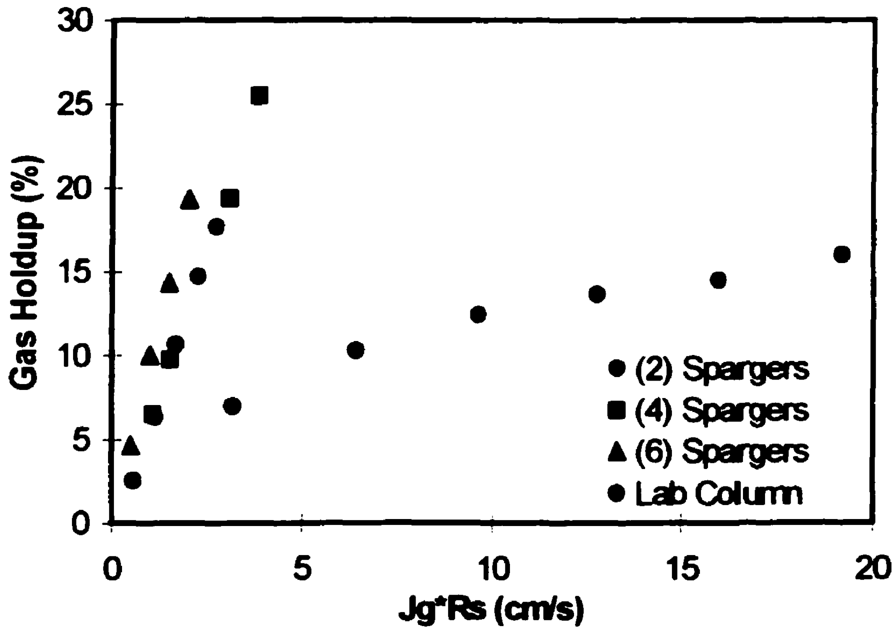

Figure 4-2: Gas holdup versus $Jg{\cdot}R_s$ for ss spargers

Table 4-1: Rs values for the stainless steel and filter cloth spargers used in the lab and pilot column.

[illegible]	[illegible]	[illegible]
2 SS	303.0	13.0
4 SS	636.0	3.1
6 SS	1075.6	1.8
Filter Cloth	4625.1	0.4
Lab Column	40.0	2.0

The other bubble generating devices used in the pilot column (jetting and filter cloth spargers) were also tested under batch conditions using water and 30 ppm of Dowfroth. The 6 ss spargers gave the highest gas holdup compared to the filter cloth and jetting sparger, with the filter cloth sparger performing better than the jetting sparger (Figure 4-3). The jetting sparger was tested in horizontal and vertical positions as there was concern that orientation would be a factor. A slight difference between the two orientations is evident, but was not considered significant enough to warrant further testing. The horizontal position was used subsequently since it could be inserted in the same ports as the ss spargers, whereas the vertical sparger would occupy the port used for the accepts stream. R_s cannot be used to characterize the jetting sparger due to the nature of the device.

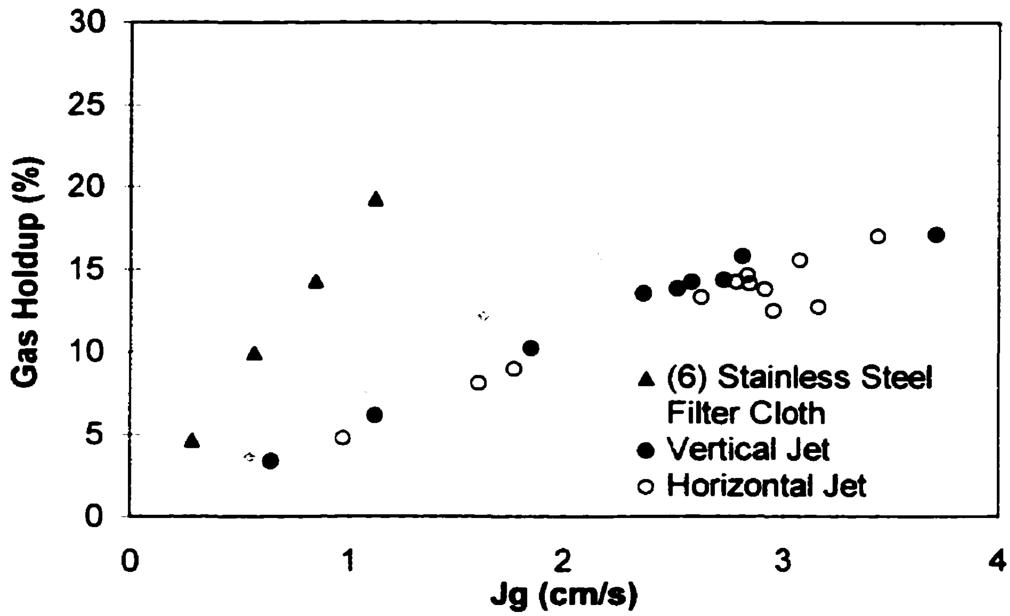

Figure 4-3: Gas holdup trends of pilot column bubble generating devices

4.3 Pulp Tests of Stainless Steel Spargers in Pilot Column

The bubble generating devices were tested using a continuous feed of pulp sampled from the feed to the Voith cells. The variables in the tests, besides the bubble generating devices, were residence time and Jg. The froth depth was kept constant at 65 cm and the pulp consistency was maintained as close to 1.0 wt% as possible. The flotation efficiency of the Voith cells was measured at the same time as the flotation column, allowing the calculation of flotation performance.

All of the data was used in the graphs of flotation performance to determine which variable gave the best correlation. This approach allows two important conclusions: how the bubble generating devices compare to another, and what is the key variable(s) related to flotation performance.

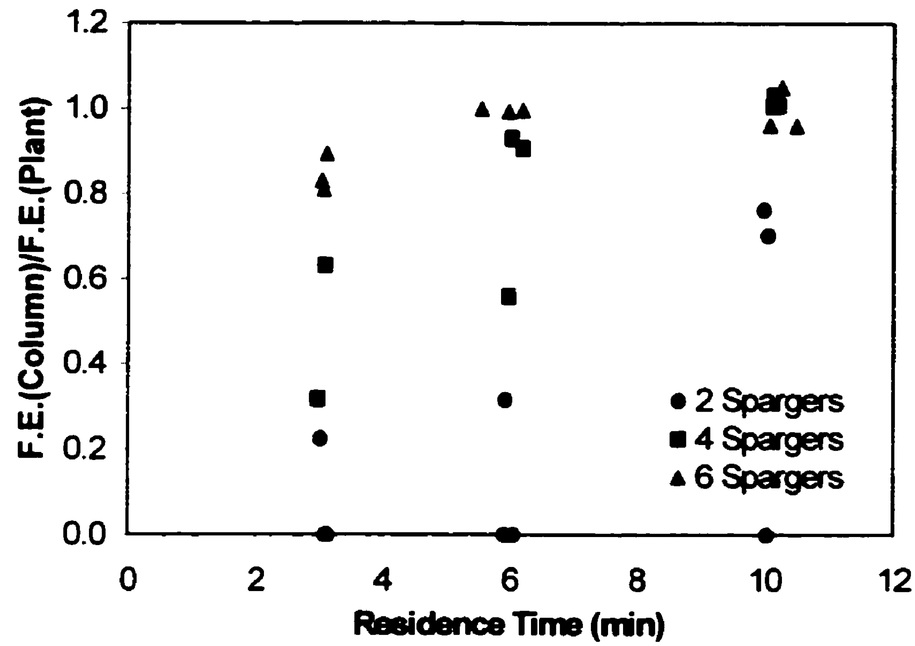

Figure 4-1: Flotation performance versus residence time for the pilot column using ss spargers (various Jg).

Graphing flotation performance versus residence time gave no indication of a discernible trend in the data as a whole (Figure 4-1). Individually, the sparger performance increased with increasing residence time despite changes in Jg. Six spargers increased flotation performance from 0.85 at a residence time of 3.0 min., to a performance matching the Voith cells at a residence time of 10.0 min. The results for 4 spargers had too much scatter to draw any quantitative conclusions, other than residence time does have an effect. Finally, it was not possible to conclude that residence time had an effect on the results for 2 spargers. This is especially true since the graph included data at three different superficial gas velocities, which could hide possible trends if the data were graphed at constant Jg.

Flotation performance versus $Jg \cdot R_s$ also did not show any trends as a whole (Figure 4-2). Individually the performance of the spargers occupied distinct areas on the graph: 6 spargers were clustered near a performance of 1.0 and a Jg*Rs of 4.0-5.0 with the results for 4 and 2 spargers having increasing amounts of scatter. The lack of simple correspondence to retention time or Jg is not unexpected. Changes in other variables, in this case bubble size resulting from the selected conditions, are also factors.

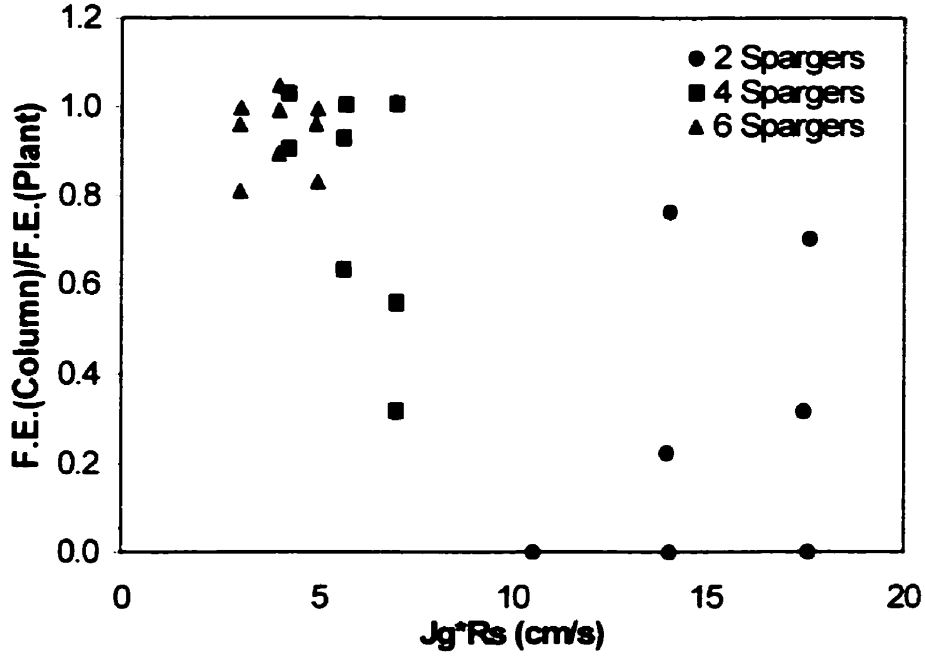

Figure 4-2: Flotation performance of the pilot column using ss spargers.

Bubble diameter, d_b, (estimated from drift flux analysis, see section 2.3) was graphed against the flotation performance (Figure 4-3). Figure 4-3 reveals an overall trend of decreasing performance as bubble size increases (except perhaps for 2 spargers case). The results for 6 and 4 spargers occupied distinct regions as in Figure 4-2. The column matched the plant efficiency at a bubble diameter $\leq$ 1.3 mm, generally corresponding to the 6 spargers. The results for 4 spargers ranged from a d_b of 0.08 cm to 0.22 cm which corresponded to a performance of 1.0 to 0.32, respectively. The 2 spargers gave flotation performances ranging from 0.76 to 0 corresponding to d_b from 0.18 cm to 0.32 cm. The results not following the trend for the 2 spargers case are for a d_b of 0.18 cm, which gave both the highest (0.76) and lowest (0.0) flotation performances.

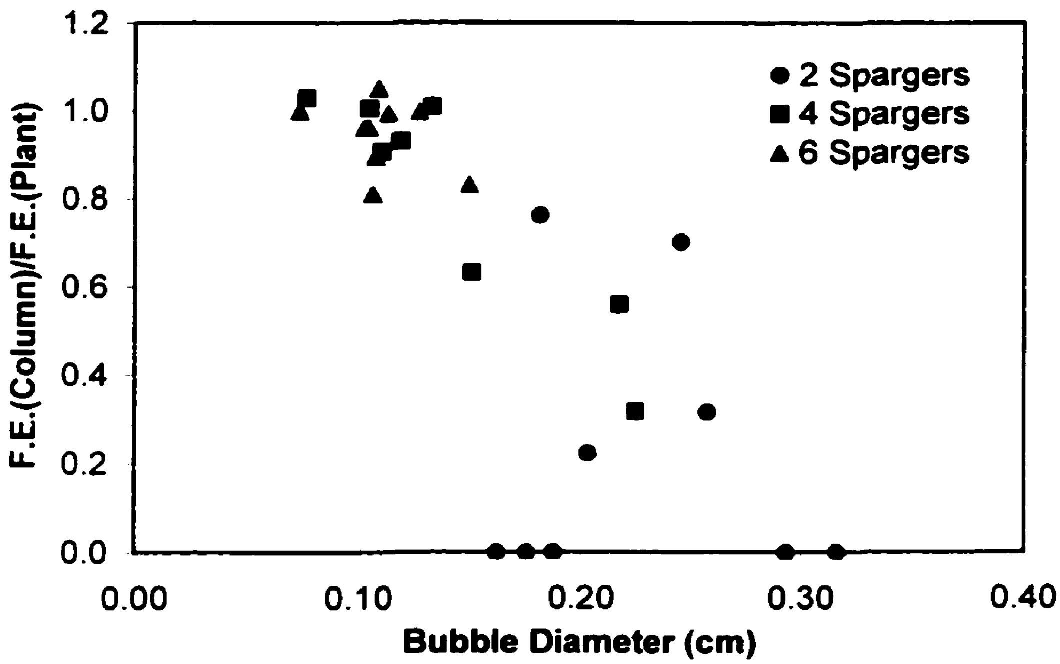

Figure 4-3: Flotation performance versus bubble diameter for the pilot column

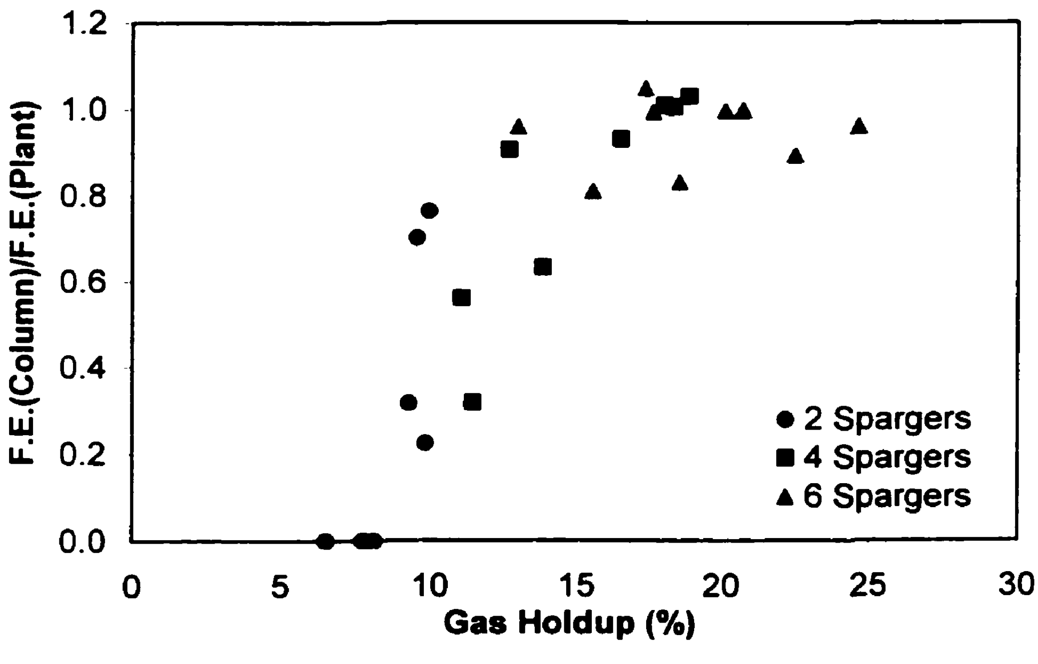

Figure 4-4: Flotation performance versus gas holdup for the pilot column.

Graphing gas holdup against flotation performance resulted in a common trend for the entire data set (Figure 4-4). At gas holdups above *ca.* 16% column flotation efficiency approached that of the Voith cells. This region is occupied by the 6 spargers, with 4 spargers ranging from 19 to 11% gas holdup and flotation performance from 1.0 to 0.3. Two spargers ranged from a gas holdup of 10 to 6.5% with flotation performance of 0.76 to 0, respectively. At gas holdups below *ca.* 9% froth would not overflow and thus flotation performance is zero. Since gas holdup, Eg, is implicitly a function of Jg (see section 4.2) and d_b, a trend between flotation performance and gas holdup is understandable.

Bubble surface area flux, Sb, as an expression is explicitly a function of Jg and d_b (see section 3.4.5). A plot of flotation performance versus Sb showed the same trend as flotation performance versus Eg, but with arguably less scatter (Figure 4-5). At an Sb greater than 100 s^{-1} the flotation performance approaches 1.0, which again was the region occupied by the 6 spargers. The results from 4 spargers fit in the middle region ranging from an Sb of 130 to 70 s^{-1}. Finally the results for 2 spargers occupied Sb ranging from 70 to 45 s^{-1} with no ink removal occurring below an Sb of approximately 50 s^{-1}.

Comparing the graphs it was evident that flotation performance was a function of Eg and Sb, independent of changes in the residence time, Jg, or number of spargers. The results of the pulp test work in the pilot column indicated that Eg $\geq$ 16% or Sb > 100 s^{-1} was required for the column to match the plant. This was consistently achieved by 6 ss spargers and sometimes by 4. These trends were anticipated by the batch test results using water and Dowfroth (see section 4.2).

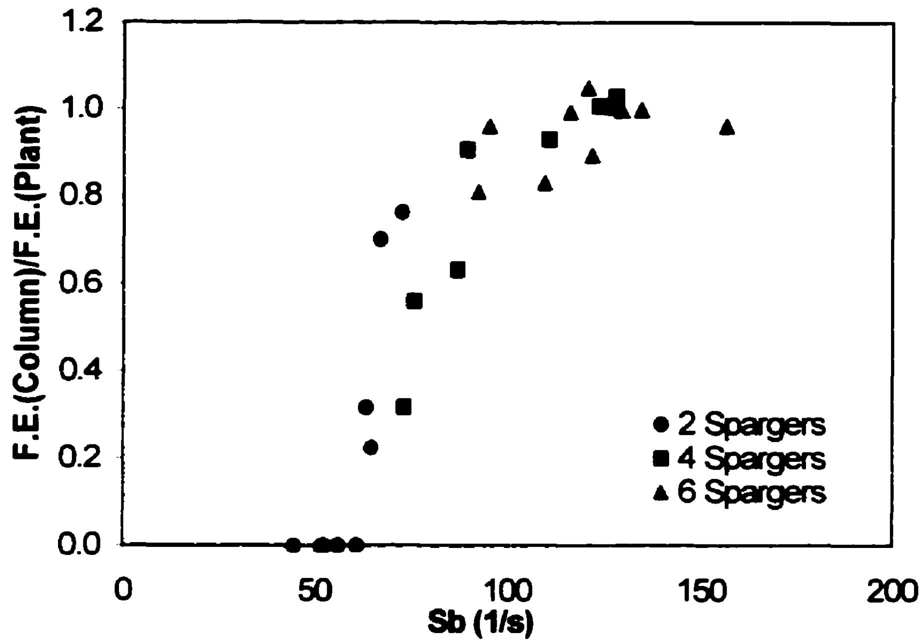

Figure 4-5: Flotation performance versus bubble surface area flux using the pilot column ss spargers

4.4 Comparison of Eg and Sb

Comparing performance as a function of Eg (Figure 4-4) and Sb (Figure 4-5) it was evident the latter showed less scatter. Curve fitting both plots using an equation normally used for cyclones and gravity concentrators:

$$Flotation\ Performance = 1 - \exp\left(-0.693\left(\frac{x}{x_{50}}\right)^{m}\right)$$

Equation 32

and plotting together indicated that the relationship with Eg and Sb are essentially the same shape (Figure 4-1). The constants in Equation 32 are given in Table 4-1 where the variable x_{50} corresponds to S_b or Eg at a ratio of 0.5 and x corresponds to the variables S_b or Eg. The Eg curve had a χ^2 of 0.036 versus a χ^2 of 0.029 for the S_b curve.

Table 4-1: Values of constants used in Equation 32.

Variable	S_b	Eg
X_{50}	72.7±1.9	10.8±0.4
M	4.18±0.65	3.66±0.63

Plotting Eg against S_b resulted in a linear relation of Sb = 5.6*Eg+7.6 and a R^2 of 0.93. The significance of the intercept at 7.6 is unexplained. On Figure 4-2, 95% confidence intervals are shown with the lower confidence interval intercepting the y-axis at 3.1 s^{-1}. It was initially believed that Sb and Eg were linearly correlated due to a mathematical effect of the drift flux model which was used in the calculation of Sb.

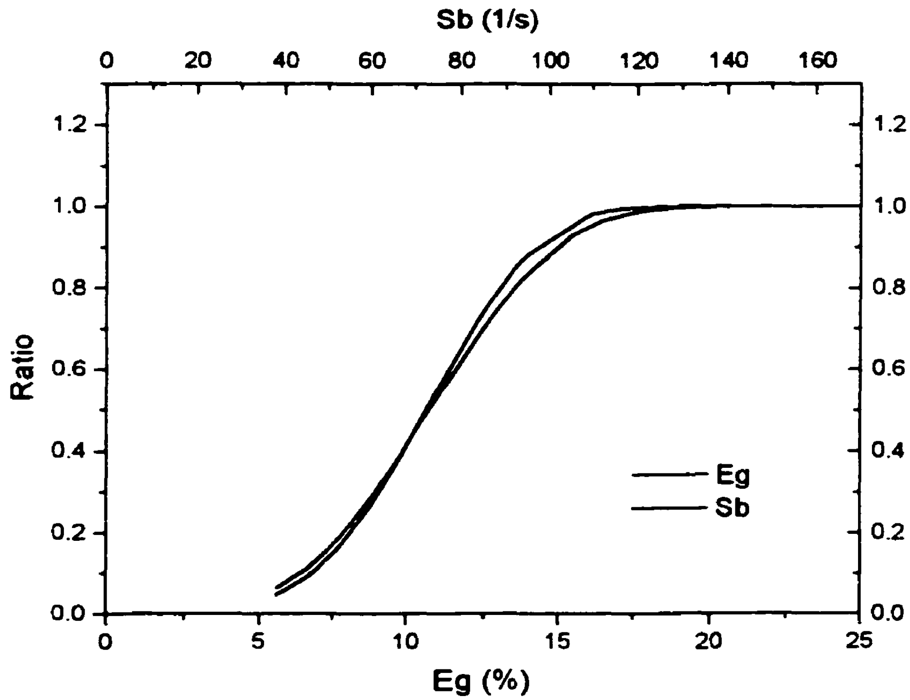

Figure 4-1: Comparison of fitted curves (Equation 32) of flotation performance versus Sb and Eg.

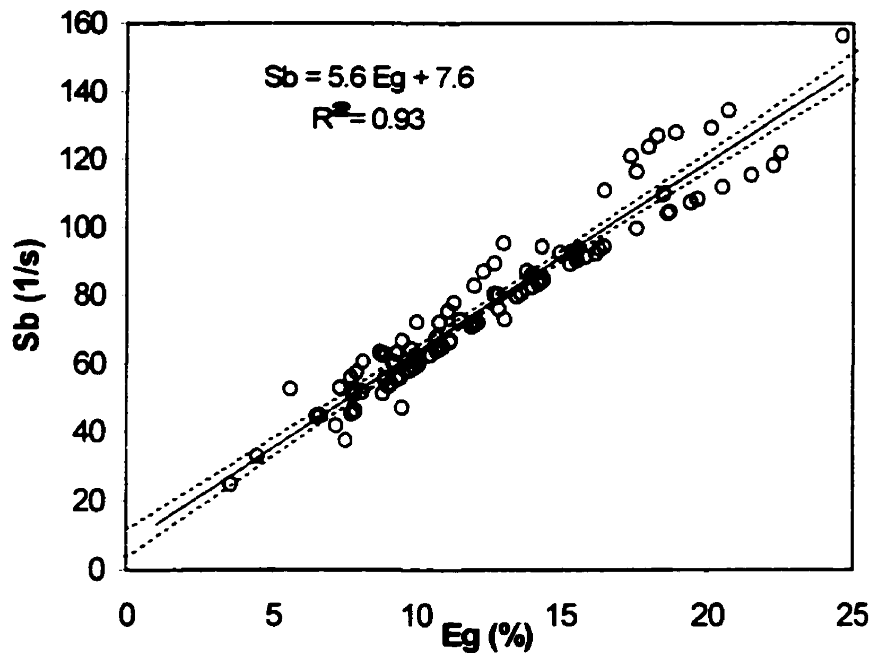

Figure 4-2: Comparison of Sb to Eg using data points from all tests (ie. laboratory and pilot scale columns).

The drift flux model is a function of Eg, Jg, and J_{Acc}, and the equation used to calculate d_b as presented in section 2.3:

$$d_b = \left[\overbrace{\frac{18\mu_{sl}}{g\,\Delta\rho}}^{k^2} \bullet U_t \bullet \overbrace{\left(1 + 0.15\,\mathrm{Re}_s^{0.687}\right)}^{c^2} \right]^{0.5}$$

Equation 8

where the pulp properties will be called k^2 and the term $(1+0.15Re_s^{0.687})$ will be approximated as a constant, c^2, to simplify the equation. Inserting Equation 8 into Sb:

$$Sb = \frac{6Jg}{c \bullet k \bullet U_t^{0.5}}$$

Equation 33

where $$U_t = \frac{U_s}{(1-Eg)^{m-1}}$$, m=3 and

Equation 3

$$U_s = \frac{Jg}{Eg} + \frac{J_{Acc}}{(1-Eg)}$$

Equation 2

Combining and simplifying gives:

$$Sb = \frac{6Eg^{0.5}}{c \bullet k \bullet \left[\frac{Jg(1-Eg) - J_{Acc}Eg}{Jg^2(1-Eg)^3}\right]^{0.5}}$$

Equation 34

From *Equation 34* it is evident that the relation between Eg and Sb is complex and non-linear. An explanation of the linearity of Figure 4-2 is hypothesized with two "effects" attributed to the phenomenon. The first effect is the range of operating variables, Jg and J_{Acc}, vary no greater in magnitude than approximately 1 to 3 cm/s, therefore acting as a minor variable in *Equation 34*. Second, Eg is a natural function of Jg and d_b as already mentioned, and changes in magnitude from 8 to 20%. Another feature of Figure 4-2 is the data appears to be comprised of two sets, one above the trend line and one below. An analysis of the data showed no distinction between the two sets either in date of experiment or in terms of Jg, J_{Acc}, or accepts consistency. The distinction is therefore attributed to an unmeasured variable (such as chemistry). In conclusion, it was felt that Sb should be used when possible, with Eg used if either accuracy was less of an issue or either Jg or d_b could not be deduced from indirect or direct measurements.

4.5 Pulp Tests in Laboratory and Pilot Columns

The continuous tests were performed on pulp drawn from the feed to the Voith cells. The experimental design used residence time and Jg as variables while keeping the froth depth constant at 65cm as done with the ss spargers. An attempt was made to keep the accepts consistency for all tests at 1.0 ± 0.2 wt%. Following the above discussion, the devices were compared on the basis of Sb. Comparing the performance of the different bubble generating devices showed that the ss spargers outperformed the other devices, being the only to attain a flotation performance of 1 (at Sb > 100 s^{-1})(Figure 4-1).

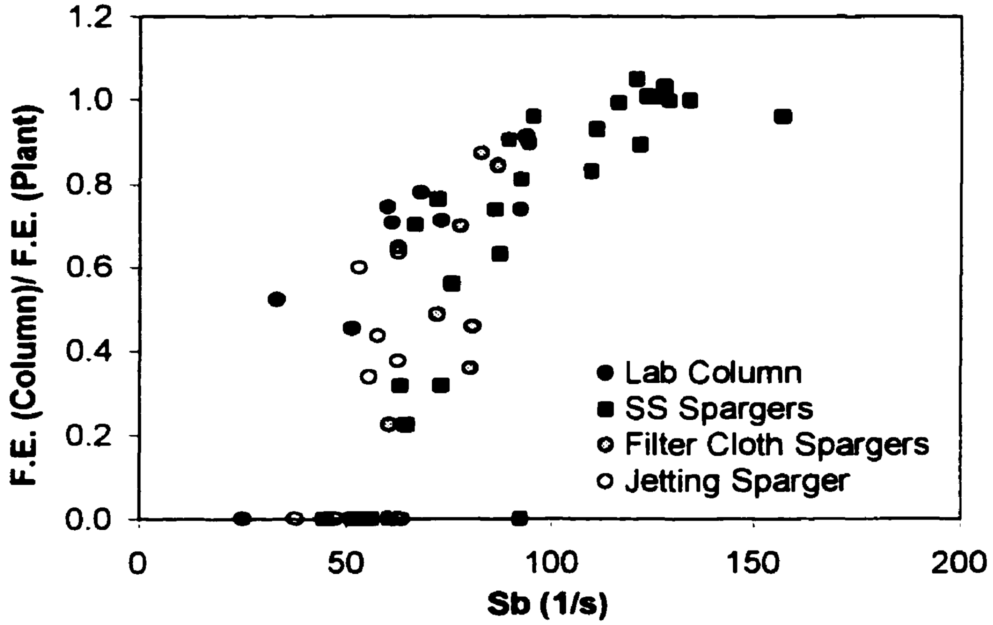

Figure 4-1: Comparison of all bubble generating devices in the pilot and laboratory columns.

The filter cloth sparger reached a maximum flotation performance of 0.87 at a Sb of 83s^{-1}, whereas the jetting sparger reached a maximum performance of 0.64 at 50s^{-1}. The laboratory column had a maximum flotation performance of 0.91 at a Sb of 94s^{-1}. From the trend of the overall curve, an Sb above 100s^{-1} is required for the flotation performance to approach that of the plant. Below 100s^{-1} the flotation performance deteriorates quickly.

At Sb < $60s^{-1}$ a difference in the trend of the laboratory and pilot column results was evident. To perform statistical analysis as to the significance of this difference it was necessary to linearize the curves. An overall flotation rate constant was calculated assuming first-order kinetics and a perfectly mixed reactor (column) (see section 2.5).

The collection zone recovery was calculated using R_{fc} and assuming a R_f of 0.5. An average liquid residence time of the collection zone was used with Equation 17 andEquation 18 to calculate the overall flotation rate constant, k_{fc}. Since the range of ink particle sizes are *ca.* 25 µm (and have a low specific gravity), the liquid residence time was assumed equal to the particle residence time [Petri, 1994]. Flotation performances approaching 0.99 were eliminated due to the asymptotic nature of the equation. For shallow froth depths k_{fc} is linearly related to Sb [Gorain *et al.*, 1997] (see also Equation 15):

$$k_{fc} = P \bullet Sb$$

Equation 35

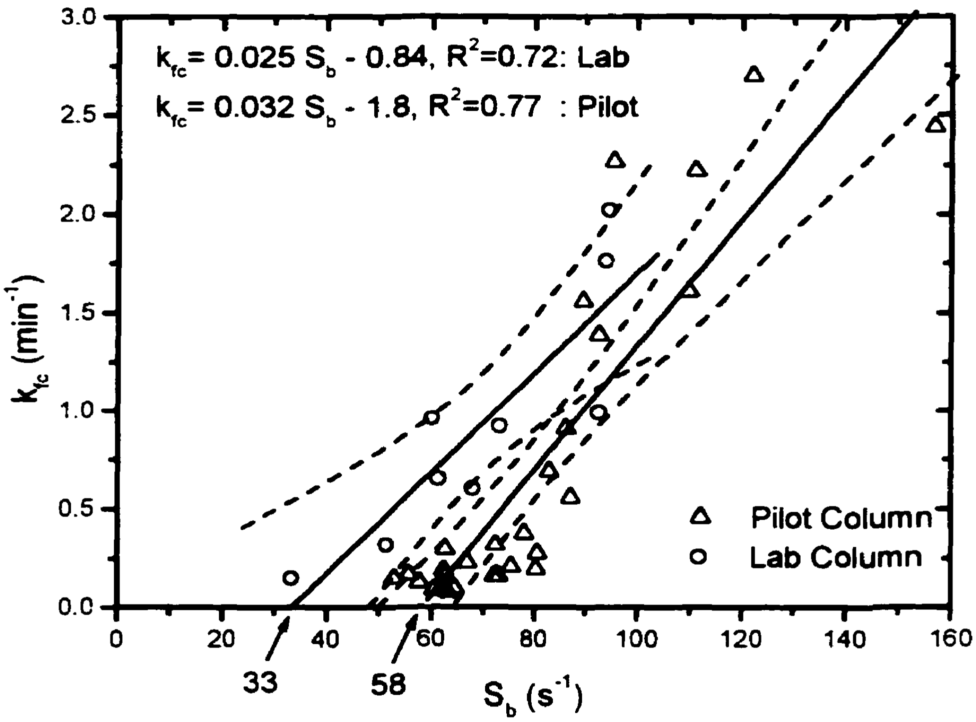

Figure 4-2: Overall flotation rate constant versus Sb

On Figure 4-2 the x-axis intercept for the lab column is 33 s^{-1} and 58 s^{-1} for the pilot column. The intercepts were independent of one another at a 95% confidence interval (which is shown in dotted red for the lab column and dotted blue for the pilot column). The physical meaning of this was that overflow did not occur until the Sb was greater than approximately 30 s^{-1} for the lab column or 60 s^{-1} for the pilot column. The differences in minimum Sb were attributed to the smaller diameter lab column supporting froths that would normally have collapsed in the pilot column (ie. a wall effect). This phenomena is only evident at low Sb; at high Sb the curves merge. Since the usual goal is to maximize flotation performance, the laboratory column under that condition accurately predicts Sb > 100 s^{-1} is required.

4.6 Long Term Tests of Bubble Generating Devices

The bubble generating devices were tested for a period of twelve hours. The motivation for these tests was experience in mineral flotation that the ss spargers deteriorate over time due to plugging. It was also hypothesized that spargers with a greater surface area would plug faster than spargers with a smaller surface area due to lower air velocities per pore (at equivalent Jg). The tests were run at constant conditions over a period of five days, with the froth depth fixed at 65 cm, Jg equal to 2.5 cm/s, and a residence time of 6 min. From Figure 4-1 it can be seen that the Sb of 6 spargers decreased over time, approaching the Sb of 4 spargers near the end of the test. The filter cloth spargers had a higher overall Sb than 2 spargers with the jetting sparger performing close to the minimum Sb for overflow. Overflow ceased before the end of the twelve hours for the jetting and 2 spargers with the test terminated 4 to 5 residence times after the overflow had stopped.

The decrease in Sb for the 6 spargers, compared to approximately constant performance for the 4 and 2 spargers, could be attributed to greater air velocities per pore of sparger for the latter two. These higher air velocities would moderate the plugging of the sparger extending the period between maintenance. Longer test periods are needed (possibly in the order of weeks) to give conclusive results.

Slight variations in the Sb resulted in significant variations in the flotation performance (Figure 4-2) for Sb between 50 and $100s^{-1}$ corresponding to the sensitive section of the flotation performance – Sb relationship (see Figure 4-1). This was most evident for the jetting and 2 sparger cases. Generally, as the accepts consistency decreased, performance increased (Figure 4-3). The inverse relationship between consistency and performance is expected given the effect of consistency on gas holdup (Figure 2-2) [Janse, 1998]. The 6 spargers gave the highest flotation performance approaching the performance of 4 spargers near the end of the twelve hours. The filter cloth outperformed the jetting and 2 spargers, in accord with the relative Sb values (Figure 4-1). The deviations in Sb for the long term tests can be attributed to changes in consistency (Figure 4-3) where the changes in the consistency corresponded inversely to changes in the Sb, which directly changed the flotation performance. (The process upset occurring at four hours for all of the data except 6 spargers is attributed to operator shift change).

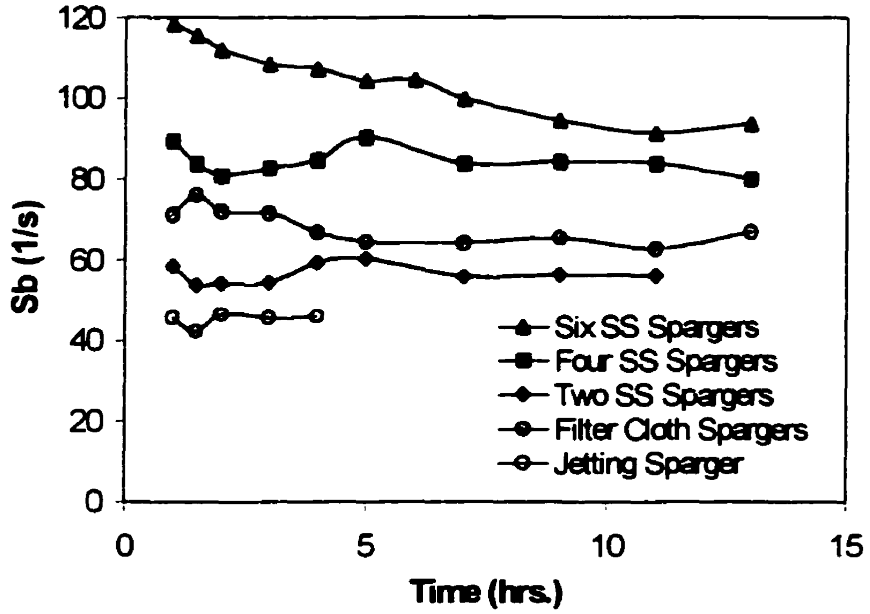

Figure 4-1: Surface Area Flux: Long term test of bubble generating devices in the pilot column

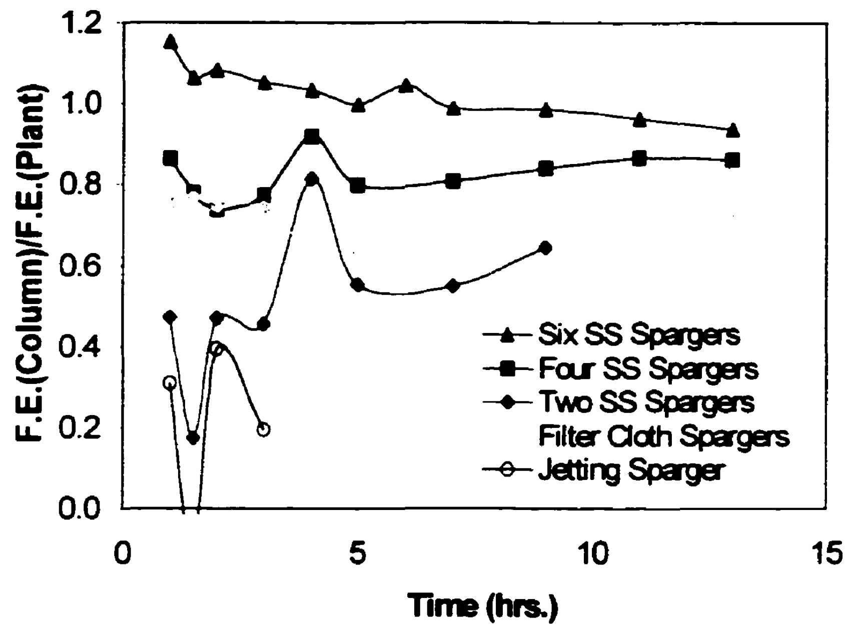

Figure 4-2: Flotation Performance: Long term test of bubble generating devices in the pilot column

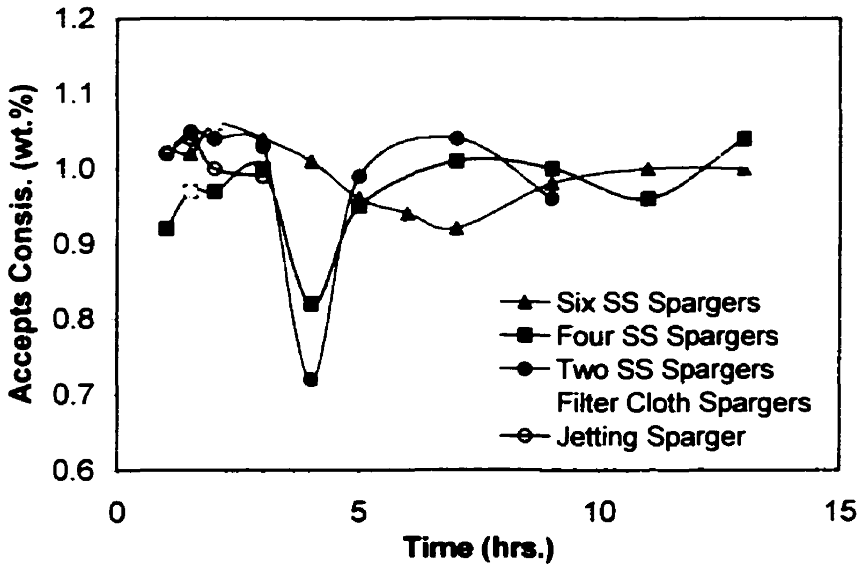

Figure 4-3: Accepts consistency: Long term test comparison of bubble generating devices.

4.7 Effects of Chemistry

Although flotation chemistry is probably not a significant factor in these tests, evidence from previous work suggests it is (as would be expected) (Figure 4-1). The operations have saved several 100,000 dollars over the past year by reducing reagent consumption [Dionne, 1997]. This appears to show as a shift in flotation efficiency to higher Sb as more bubble surface area is required to compensate for reduced ink floatability. From Figure 4-1 the previous work [Watson, 1997] indicates that the plant flotation efficiency could then be reached at an Sb of approximately 40s^{-1} versus the present 100s^{-1}.

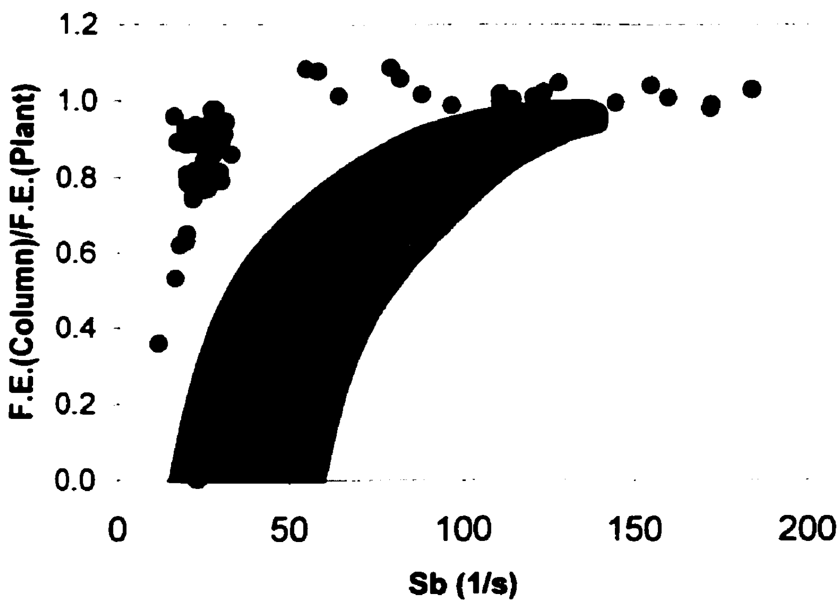

Figure 4-1: Comparison of previous results [Watson, 1997] with present results (shaded) to indicate effects of chemistry on performance.

5. CONCLUSIONS

Evaluation of the Voith Cells

The average maximum efficiency of the column and plant was 81.3% with an absolute standard deviation (abs. stdev.) of 1.1% (Figure 4-1). The plant flotation efficiency over the same period was 78.6% (abs. stdev., 1.5%). A comparison of the means suggested the difference was not significant and that the plant was operating at or near the maximum flotation efficiency. The ratio between the column and plant data was used to reduce 'noise', termed flotation performance.

Batch Tests of Laboratory and Pilot Columns

The ss spargers for the pilot column were tested under batch conditions using water with 30 ppm Dowfroth as frother. The results indicated that 4 ss spargers gave a better gas holdup trend than 6 ss spargers and significantly outperformed 2 ss spargers. The lab column gave gas holdups intermediate to the 2 ss spargers and 4 or 6 spargers in the pilot column.

The data was replotted using $Jg \cdot R_s$ with 6 spargers giving a higher gas holdup than 4 or 2 spargers at equivalent $Jg \cdot R_s$. The results for the 4 spargers gave a trend equivalent to the lab column.

A plot of Eg versus Jg including the jetting and filter cloth spargers indicated that the 6 ss spargers gave the highest gas holdup, with the filter cloth sparger performing better than the jetting sparger.

Pulp Tests of Stainless Steel Spargers in the Pilot Column

Graphing gas holdup against flotation performance resulted in a narrow band with a definite shape for the entire data set, with 6, 4, and 2 sparger sets occupying distinct regions.

A plot of flotation performance versus Sb showed the same trend as the plot of flotation performance versus Eg, but with less scatter.

Comparing the graphs it was evident that flotation performance was a function of Eg and Sb, independent of changes in the residence time, Jg, or number of spargers. The results indicated that Eg $\geq$ *ca.* 16% or Sb > 100 s^{-1} was required for the column to match the plant. This was consistently achieved by 6 ss spargers and sometimes by 4. The trends were anticipated by the batch test results using water and Dowfroth.

Comparison of Eg and Sb

Comparing performance as a function of Eg and Sb it was evident the latter had less scatter although both showed essentially the same trend. Plotting Eg against Sb resulted in a linear relation. The Sb is preferred with Eg used if Jg or d_b cannot be deduced from indirect or direct measurements.

Pulp Tests in Lab and Pilot Column

Comparing the performance of the different bubble generating devices showed that the ss spargers outperformed the other devices, being the only ones to attain a flotation performance of 1 (at Sb > 100 s^{-1}).

From a comparison of the laboratory and pilot column it was determined that overflow did not occur until the Sb was greater than *ca.* 30 s^{-1} for the lab column or *ca.* 60 s^{-1} for the pilot column. The differences in minimum Sb were attributed to the smaller diameter lab column supporting froths that would normally have collapsed in the pilot column (ie. a wall effect).

Long Term Tests

A comparison of the bubble generating devices over a period of twelve hours indicated 6 spargers plugged faster than the other ss spargers. The decrease in Sb for the 6 spargers, compared to approximately constant performance for the 4 and 2 spargers, was attributed to greater air velocities per pore of sparger for the latter two. These higher air velocities moderated the plugging of the sparger; however longer test periods are needed (in the order of weeks) to give conclusive results.

Deviations in Sb were attributed to changes in consistency which changed the gas holdup and hence flotation performance. Variations in Sb were most evident for bubble generating devices operating in the sensitive region of the flotation performance – Sb curve.

Effects of Chemistry

Reduced reagent consumption appeared to have shifted the flotation efficiency to higher Sb as more bubble surface area is required to compensate for reduced ink floatability. Previous work indicated that the plant flotation efficiency was reached at an Sb of approximately 40s^{-1} versus the present 100s^{-1}.

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7. APPENDICES

Table 7-1: Summary of Maximum Flotation Efficiency Data

Sample	Flotation Efficiency Column	Std.	Plant	Std.	τ	Ratio
5_13AB	79.58	0.79	76.80	1.24	2.62	1.04
5_22AD	81.72	0.25	80.04	1.22	2.84	1.02
5_13CF	82.43	1.32	79.94	1.79	8.20	1.03
5_14AD	81.62	0.38	78.90	1.34	8.26	1.03
5_21AD	81.01	1.85	77.27	7.04	12.06	1.05
Average:	81.27		78.59			
Stdev:	1.07		1.50			

Table 7-2:Summary of SS Sparger Gas Holdup Data

Spgrs	Jg@STP	Eg	Std
6	0.6	10.0	0.1
	1.1	19.3	0.2
	0.3	4.6	0.2
	0.8	14.3	0.1
4	0.5	9.8	0.1
	1.1	19.3	0.1
	1.4	25.5	0.2
	0.4	6.5	0.1
2	2.2	13.6	0.1
	0.5	7.0	0.1
	3.3	15.9	0.2
	1.6	12.4	0.2
	1.1	10.3	0.1
	2.7	14.4	0.2

Table 7-3: Summary of Filter Cloth, Jetting and Laboratory Column Gas Holdup Data

Type	Jg@STP	Eg	Std.	Type	Jg@STP	Eg	Std.
Filter Cloth	0.5	3.6	0.1	*Horiz. Jet*	1.0	4.7	0.2
	1.1	7.6	0.1		1.6	8.1	0.1
	1.1	8.0	0.1		1.8	9.0	0.1
	1.6	12.1	0.1		2.6	13.3	0.2
	2.2	15.5	0.1		2.8	14.2	0.2
	2.2	16.0	0.1		2.8	14.6	0.2
	2.4	18.0	0.1		2.8	14.1	0.2
					2.9	13.8	0.2
(6) SS	0.3	4.6	0.2		3.0	12.5	0.2
	0.6	10.0	0.1		3.1	15.5	0.1
	0.8	14.3	0.1		3.2	12.7	0.3
	1.1	19.3	0.2		3.4	17.0	0.3
Lab Column	0.3	2.5	0.1	*Vert. Jet*	0.6	3.4	0.2
	0.6	6.3	0.1		1.1	6.1	0.1
	0.8	10.6	0.1		1.8	10.3	0.3
	1.1	14.7	0.1		2.4	13.5	0.2
	1.3	17.6	0.2		2.5	13.8	0.2
					2.6	14.2	0.4
					2.7	14.3	0.2
					2.8	15.8	0.4
					3.7	17.1	0.4

Table 7-4: Summary of Laboratory Column Pulp Tests

Sample	pgrs	τ	Jg@STP	Jww	Jl	Eg	db@STP	Sb	Flotation Efficiency				
									Clmn	Std.	Plnt	Std.	Ratio
		min	cm/s	cm/s	cm/s	%	cm	1/s	%		%		
3_25GI	1	4.5	1.1	0.16	1.6	3.5	0.27	25	0.0	0.0	N/A	N/A	0.00
3_25DF	1	7.0	1.1	0.16	1.0	4.4	0.20	33	39.1	5.1	75.1	0.6	0.52
10_22AC	1	2.5	2.1	0.16	2.4	8.8	0.24	51	34.0	4.0	75.2	1.0	0.45
3_24DF	1	3.0	1.1	0.16	2.2	9.2	0.11	60	58.0	2.4	78.1	1.0	0.74
11_10AC	1	3.7	1.7	0.15	1.6	10.0	0.17	61	50.1	5.0	71.0	9.4	0.71
10_28AC	1	5.9	2.0	0.17	1.0	10.7	0.18	68	65.3	5.0	83.7	0.2	0.78
10_27AC	1	2.7	2.8	0.18	2.2	13.0	0.23	73	51.8	2.9	73.0	2.7	0.71
3_24AC	1	2.9	2.8	0.16	2.2	15.0	0.18	92	54.1	13.7	73.2	6.2	0.74
3_25AC	1	4.3	2.8	0.17	1.5	14.3	0.17	94	70.4	0.2	78.5	0.7	0.90
10_23AC	1	5.9	2.8	0.16	1.0	15.6	0.18	94	72.0	0.8	79.0	1.7	0.91

Note: Washwater flowrates taken by hand

Table 7-5: Summary of Pilot Column Pulp Tests (SS Spargers)

SS Porous Spargers

									Flotation Efficiency				
Sample	***pgrs***	***τ***	***g@STP***	***Jww***	***Jl***	***Eg***	***db@STP***	***Sb***	***Clmn***	***Std.***	***Plnt***	***Std.***	***Ratio***
		min	***cm/s***	***cm/s***	***cm/s***	***%***	***cm***	***1/s***	***%***		***%***		
2_5NOFLW	2	5.9	2.2	0.18	1.2	6.5	0.29	45	0.0	0.0	n/a	n/a	0.00
2_6NOFLW	2	3.1	2.7	0.05	2.2	8.1	0.32	52	0.0	0.0	n/a	n/a	0.00
2_7NOFLW2	2	3.1	1.6	0.14	2.2	7.8	0.19	53	0.0	0.0	n/a	n/a	0.00
11_25DF2	2	6.1	1.6	n/a	1.1	7.7	0.18	56	0.0	0.0	n/a	n/a	0.00
2_7NOFLW	2	10.0	1.6	0.14	0.7	8.1	0.16	61	0.0	0.0	n/a	n/a	0.00
11_28DF	2	5.9	2.7	0.09	1.1	9.3	0.26	63	26.1	6.1	82.5	1.4	0.32
11_27AC	2	3.0	2.2	0.14	2.2	9.8	0.20	64	17.8	3.3	79.7	0.2	0.22
11_21DF	2	10.1	2.7	0.11	0.7	9.5	0.25	67	59.0	5.8	84.0	1.3	0.70
11_23AC	2	10.0	2.2	0.16	0.7	10.0	0.18	72	60.3	3.6	79.1	4.5	0.76
2_4DF	4	3.0	2.7	0.16	2.2	11.5	0.22	73	23.9	7.3	75.1	1.1	0.32
2_4AC	4	6.0	2.7	0.14	1.1	11.1	0.22	76	38.1	13.6	68.1	1.7	0.56
2_8AC	4	3.1	1.6	0.14	2.1	14.0	0.11	86	56.7	1.1	76.8	0.3	0.74
2_5AC	4	3.1	2.2	0.20	2.1	13.8	0.15	87	48.0	7.3	75.9	0.6	0.63
11_21GI	4	6.2	1.6	0.13	1.0	12.7	0.11	90	75.2	1.9	83.0	0.8	0.91
11_25AC	4	6.0	2.2	0.10	1.0	16.5	0.12	111	77.5	1.4	83.3	0.7	0.93
11_23JL	4	10.2	2.7	0.16	0.6	18.0	0.13	124	83.7	1.2	83.1	0.8	1.01
11_23DF	4	10.1	2.2	0.16	0.6	18.3	0.10	127	82.2	0.8	81.8	0.9	1.01
11_23GI	4	10.1	1.6	0.16	0.6	18.9	0.08	128	86.1	0.6	83.6	0.6	1.03
2_7DF	6	3.1	1.6	0.15	2.0	15.5	0.11	93	58.1	1.6	71.6	5.6	0.81
2_6DF	6	10.5	1.6	0.09	0.6	13.0	0.10	95	77.6	3.2	80.9	0.9	0.96
2_6AC	6	3.0	2.7	0.10	2.0	18.5	0.15	110	63.2	5.6	76.1	3.0	0.83
2_5DF	6	6.0	2.2	0.17	1.0	17.6	0.11	116	75.6	1.0	76.2	0.8	0.99
2_7AC	6	10.3	2.2	0.15	0.6	17.4	0.11	121	80.9	0.7	77.2	0.4	1.05
11_25DF	6	3.1	2.2	0.15	1.8	22.5	0.11	122	72.1	2.7	80.7	0.4	0.89
2_7GI	6	6.2	2.7	0.17	0.9	20.1	0.13	129	75.5	0.6	75.8	1.1	1.00
11_21AC	6	5.5	1.7	0.23	0.7	20.7	0.07	134	81.9	2.2	82.1	2.4	1.00
11_28AC	6	10.1	2.7	0.21	0.6	24.6	0.10	157	80.6	2.3	83.8	1.1	0.96

Table 7-6: Summary of Pilot Column Pulp Tests (Filter Cloth and Jetting Spargers)

Filter Cloth Sparger

									Flotation Efficiency:				
Sample	***Spgrs***	***τ***	***Jg@STP***	***Jww***	***Jl***	***Eg***	***b@STP***	***Sb***	***Clmn***	***Std.***	***Plnt***	***Std.***	***Ratio***
		min	***cm/s***	***cm/s***	***cm/s***	***%***	***cm***	***1/s***	***%***		***%***		
5_6DF	5	3.1	2.2	0.16	2.2	9.2	0.22	60	17.1	13.4	76.0	2.4	0.22
5_6AC	5	6.1	2.2	0.11	1.1	8.9	0.21	63	49.5	2.5	76.5	0.7	0.65
5_7NFLW	5	10.0	2.2	0.11	0.7	8.7	0.21	63	0.0	0.0	n/a	n/a	0.00
5_5AC	5	6.0	3.3	0.13	1.1	10.8	0.27	72	37.8	1.0	77.7	0.5	0.49
5_7GI	5	6.0	2.7	0.12	1.1	11.3	0.21	78	52.7	2.2	75.5	1.9	0.70
5_4AC	5	2.8	3.3	0.12	2.2	12.8	0.24	80	25.2	8.1	70.5	6.0	0.36
5_7DF	5	3.0	2.7	0.17	2.2	12.7	0.20	81	33.7	8.0	73.6	5.0	0.46
5_7AC	5	10.0	3.3	0.10	0.6	12.0	0.24	83	65.2	2.4	74.7	0.1	0.87
5_5DF	5	9.8	2.7	0.13	0.7	12.3	0.19	87	69.0	2.1	81.7	1.1	0.84

Jetting Sparger

									Flotation Efficiency:				
Sample	***prgrs***	***τ***	***Jg@STP***	***Jww***	***Jl***	***Eg***	***b@STP***	***Sb***	***Clmn***	***Std.***	***Plnt***	***Std.***	***Ratio***
		min	***cm/s***	***cm/s***	***cm/s***	***%***	***cm***	***1/s***	***%***		***%***		
_25NOF	1	3.1	1.7	0.12	2.2	5.6	0.26	38	0.0	0.0	n/a	n/a	0.00
_27NFL	1	6.0	2.5	0.07	1.1	6.6	0.33	45	0.0	0.0	n/a	n/a	0.00
_26NFL	1	3.1	2.6	0.07	2.2	7.3	0.34	47	0.0	0.0	n/a	n/a	0.00
_27NFW	1	6.0	3.1	0.07	1.1	7.8	0.36	51	0.0	0.0	n/a	n/a	0.00
_25NFW	1	10.6	2.5	0.09	0.7	7.5	0.29	53	0.0	0.0	n/a	n/a	0.00
3_26MO	1	9.8	3.1	0.09	0.7	7.9	0.36	53	46.2	0.9	77.2	0.8	0.60
3_26GI	1	3.0	3.1	0.08	2.2	8.8	0.33	56	25.0	7.5	74.1	1.1	0.34
3_26JL	1	6.0	3.8	0.08	1.1	8.9	0.39	58	32.5	6.9	74.7	0.8	0.44
3_26AC	1	3.2	3.7	0.07	2.1	10.0	0.35	62	28.9	7.4	77.0	2.4	0.38
3_26DF	1	11.1	3.8	0.06	0.6	9.5	0.36	63	50.1	7.4	78.7	5.5	0.64

Note: The washwater flowrates marked in red were measured by hand.

Table 7-7: Summary of Long Term Tests

Type	***Time***	***Acc Consis***	***Eg***	***Jg@STP***	***Jl***	***Sb***	***Clmn***	***Plnt***	***Ratio***
	hrs.	***%***	***%***	***cm/s***	***cm/s***	***1/s***	***%***	***%***	
Six SS Spargers	1.0	1.0	22.2	2.7	1.0	118	77.3	67.1	1.15
	1.5	1.0	21.5	2.7	1.0	116	75.8	71.2	1.06
	2.0	1.1	20.5	2.7	1.0	112	75.2	69.4	1.08
	3.0	1.0	19.6	2.7	1.0	109	76.3	72.5	1.05
	4.0	1.0	19.4	2.7	1.0	107	74.9	72.5	1.03
	5.0	1.0	18.6	2.7	1.0	104	72.9	73.0	1.00
	6.0	0.9	18.7	2.7	1.0	105	76.8	73.5	1.05
	7.0	0.9	17.6	2.7	1.0	100	70.6	71.4	0.99
	9.0	1.0	16.5	2.7	1.0	94	69.2	70.2	0.99
	11.0	1.0	15.8	2.7	1.0	91	72.7	75.5	0.96
	13.0	1.0	16.3	2.7	1.0	94	67.5	72.0	0.94
Four SS Spargers	1.0	0.9	15.3	2.7	1.0	89	64.1	74.1	0.86
	1.5	1.0	14.2	2.7	1.1	84	55.9	71.7	0.78
	2.0	1.0	13.6	2.7	1.1	81	52.7	71.5	0.74
	3.0	1.0	14.0	2.7	1.1	83	57.7	74.6	0.77
	4.0	0.8	14.4	2.7	1.1	85	71.7	78.0	0.92
	5.0	1.0	15.5	2.7	1.1	90	62.0	77.5	0.80
	7.0	1.0	14.2	2.7	1.1	84	60.3	74.7	0.81
	9.0	1.0	14.3	2.7	1.1	84	64.0	76.2	0.84
	11.0	1.0	14.2	2.7	1.1	84	67.3	77.6	0.87
	13.0	1.0	13.5	2.7	1.1	80	65.7	76.3	0.86

(Summary of Long Term Tests, cont.'d):

Type	Time hrs.	Acc Consis %	Eg %	Jg@STP cm/s	Jl cm/s	Sb 1/s	Clmn %	Plnt %	Ratio
Two SS Spargers	1.0	1.0	9.8	2.7	1.1	58	32.7	69.3	0.47
	1.5	1.1	9.0	2.7	1.1	54	12.2	70.2	0.17
	2.0	1.0	9.1	2.7	1.1	54	33.0	70.4	0.47
	3.0	1.0	9.1	2.7	1.1	54	31.3	68.6	0.46
	4.0	0.7	9.9	2.7	1.1	59	53.0	65.3	0.81
	5.0	1.0	10.1	2.7	1.1	60	41.0	74.3	0.55
	7.0	1.0	9.3	2.7	1.1	56	41.1	74.9	0.55
	9.0	1.0	9.4	2.7	1.1	56	48.5	75.2	0.65
	11.0	n/a	9.4	2.7	1.1	56	n/a	n/a	n/a
Jetting	1.0	1.0	7.7	2.7	1.1	46	21.8	70.4	0.31
	1.5	1.0	7.2	2.7	1.1	42	-7.7	71.4	-0.11
	2.0	1.0	7.8	2.7	1.1	46	29.3	74.2	0.39
	3.0	1.0	7.7	2.7	1.1	45	14.4	73.7	0.20
	4.0	n/a	7.8	2.7	1.1	46	n/a	n/a	n/a
Filter Cloth	1.0	1.0	11.9	2.7	1.1	71	57.0	75.7	0.75
	1.5	1.0	12.8	2.7	1.1	76	56.9	74.1	0.77
	2.0	1.1	12.1	2.7	1.1	72	55.0	73.8	0.75
	3.0	1.1	12.0	2.7	1.1	72	55.1	73.9	0.75
	4.0	1.2	11.2	2.7	1.1	67	47.8	75.5	0.63
	5.0	1.1	10.8	2.7	1.1	64	47.1	74.8	0.63
	7.0	1.1	10.7	2.7	1.1	64	46.6	75.4	0.62
	9.0	1.1	10.9	2.7	1.1	65	40.9	77.1	0.53
	11.0	1.0	10.5	2.7	1.1	63	43.7	77.2	0.57
	13.0	1.0	11.2	2.7	1.1	67	54.6	74.3	0.73

Table 7-8: Summary of Flotation Rate Constants

			Flotation Efficiency							
Sample	***Spgrs***	***Sb***	***Clmn***	***Std***	***Plnt***	***Std***	τ	***R(fc)***	***R(c)***	***k(fc)***
SS Spargers										
11_28DF	2	63.2	26.1	6.1	82.5	1.4	5.9	0.32	0.48	0.08
11_27AC	2	64.4	17.8	3.3	79.7	0.2	3.0	0.22	0.37	0.10
11_21DF	2	66.9	59.0	5.8	84.0	1.3	10.1	0.70	0.82	0.23
11_23AC	2	72.4	60.3	3.6	79.1	4.5	10.0	0.76	0.87	0.32
2_4DF	4	73.0	23.9	7.3	75.1	1.1	3.0	0.32	0.48	0.16
2_4AC	4	75.6	38.1	13.6	68.1	1.7	6.0	0.56	0.72	0.21
2_8AC	4	86.1	56.7	1.1	76.8	0.3	3.1	0.74	0.85	0.91
2_5AC	4	87.1	48.0	7.3	75.9	0.6	3.1	0.63	0.77	0.56
11_21GI	4	89.5	75.2	1.9	83.0	0.8	6.2	0.91	0.95	1.56
2_7DF	6	92.6	58.1	1.6	71.6	5.6	3.1	0.81	0.90	1.39
2_6DF	6	95.5	77.6	3.2	80.9	0.9	10.5	0.96	0.98	2.27
2_6AC	6	109.8	63.2	5.6	76.1	3.0	3.0	0.83	0.91	1.61
11_25AC	4	111.0	77.5	1.4	83.3	0.7	6.0	0.93	0.96	2.22
11_25DF	6	122.0	72.1	2.7	80.7	0.4	3.1	0.89	0.94	2.70
11_28AC	6	156.7	80.6	2.3	83.8	1.1	10.1	0.96	0.98	2.44
Jetting Sparger										
3_26MO	1	53.0	46.2	0.9	77.2	0.8	9.8	0.60	0.75	0.15
3_26GI	1	55.7	25.0	7.5	74.1	1.1	3.0	0.34	0.50	0.17
3_26JL	1	57.7	32.5	6.9	74.7	0.8	6.0	0.44	0.61	0.13
3_26AC	1	62.4	28.9	7.4	77.0	2.4	3.2	0.38	0.55	0.19
3_26DF	1	62.7	50.1	7.4	78.7	5.5	11.1	0.64	0.78	0.16

(Summary of Flotation Rate Constants, cont.'d)

		Flotation Efficiency								
Sample	***Sprgs***	***Clmn***	***Std***	***Plnt***	***Std***	***Sb***	τ	***R(fc)***	***R(fc)***	***k(fc)***
Filter Cloth Spagers										
5_6DF	1	60.5	17.1	13.4	76.0	2.4	3.1	0.22	0.37	0.09
5_6AC	1	62.7	49.5	2.5	76.5	0.7	6.1	0.65	0.79	0.30
5_7NFLW	1	63.4	0.0	0.0	N/A	N/A	10.0	0.00	0.00	0.00
5_5AC	1	72.1	37.8	1.0	77.7	0.5	6.0	0.49	0.65	0.16
5_7GI	1	77.9	52.7	2.2	75.5	1.9	6.0	0.70	0.82	0.38
5_4AC	1	80.3	25.2	8.1	70.5	6.0	2.8	0.36	0.53	0.20
5_7DF	1	80.6	33.7	8.0	73.6	5.0	3.0	0.46	0.63	0.28
5_7AC	1	82.9	65.2	2.4	74.7	0.1	10.0	0.87	0.93	0.69
5_5DF	1	87.0	69.0	2.1	81.7	1.1	9.8	0.84	0.92	0.56
Lab Collumn										
10_22AC	1	34.0	4.0	75.2	1.0	51.4	2.5	0.45	0.62	0.32
10_23AC	1	72.0	0.8	79.0	1.7	93.8	5.9	0.91	0.95	1.76
10_27AC	1	51.8	2.9	73.0	2.7	73.1	2.7	0.71	0.83	0.92
10_28AC	1	65.3	5.0	83.7	0.2	67.9	5.9	0.78	0.88	0.60
11_10AC	1	50.1	5.0	71.0	9.4	61.2	3.7	0.71	0.83	0.65
3_24AC	1	54.1	13.7	73.2	6.2	92.5	2.9	0.74	0.85	0.99
3_24DF	1	58.0	2.4	78.1	1.0	60.1	3.0	0.74	0.85	0.96
3_25AC	1	70.4	0.2	78.5	0.7	94.5	4.3	0.90	0.95	2.02
3_25DF	1	39.1	5.1	75.1	0.6	33.2	7.0	0.52	0.69	0.15

Note: R(f) assumed to be equal to 0.5

Table 7-9: Summary of Previous Work (source: Watson, 1996)

Open Laboratory Column

Sb	Ratio
154	1.04
64	1.01
110	1.02
81	1.06
127	1.05
123	1.02
159	1.01
183	1.03
144	1.00
172	0.99
171	0.98
122	0.99
110	1.00
113	1.00
120	1.01
96	0.99
87	1.02
18	0.62
12	0.36
24	0.82
26	0.89
26	0.82
23	n/a
22	0.76
26	0.90
20	0.65
20	0.78
25	0.83
19	0.63
20	0.78

Open Pilot Column

Sb	Ratio
21	0.75
22	0.94
22	0.77
22	0.82
23	0.89
19	0.81
23	0.80
25	0.90
25	0.81

Packed Laboratory Column

Sb	Ratio
54	1.08
78	1.09
58	1.08
16	0.96
27	0.86
30	0.91
16	0.53
28	0.91
28	0.98
32	0.86
30	0.90
29	0.81
31	0.95
30	0.79
21	0.74
27	0.97
24	0.89
28	0.94
25	0.81
26	0.92
26	0.77
25	0.91
26	0.98

Packed Pilot Column

Sb	Ratio
19	0.89
17	0.89
19	0.93
21	0.89
25	0.89
27	0.88
24	0.92
26	0.94
28	0.93
29	0.93
27	0.88
26	0.89
28	0.87
26	0.86
25	0.85
25	0.77

Table 7-10: Statistical Analysis of Ratio Expression

Sample	***Clmn***	***Ratio***
2.62	76.8	1.04
2.84	80.0	1.02
Average:	78.4	1.03
Abs. St. Dev.:	2.3	0.01
Rel. St. Dev.:	2.9%	1.4%
8.2	79.9	1.03
8.25	78.9	1.03
Average:	79.4	1.03
Abs. St. Dev.:	0.7	0.00
Rel. St. Dev.:	0.9%	0.0%
Overall		
Average:	78.9	1.03
Abs. St. Dev.:	1.5	0.01
Rel. St. Dev.:	1.9%	0.79%
Variance:	3.63E-04	6.28E-05

Test Statistic (s1^2/s2^2): 5.78

d.f.(Column): 3

d.f.(Ratio): 3

Probability Population St. Dev. are not equal: 90.8%

Assumption(s):

Population standard deviations at 8 min. and 2 min. are equal.

Residence time does not have an effect on column flotation efficie

Values are normally distributed.