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Deinking Recycled Paper Using Column Flotation

Jeffrey A. Watson

Department of Mining and Metallurgical Engineering
McGill University
Montreal, Canada

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Abstract

The degree of waste paper recycling has been increasing steadily in North America over the last decade. Flotation is a popular method for removing ink from fibres (deinking) and is traditionally performed in mechanical cells. Column flotation has been proposed as an alternative to mechanical cells. In this work, open and packed laboratory and pilot-scale columns were operated to determine their relative merits and how they compare to a circuit of mechanical cells

It was found that the type of sparger was critical for obtaining high flotation efficiencies. Fine porous stainless steel spargers (0.5 μm) produced flotation efficiencies which were equal to those of the mechanical cells. Packing was effective in increasing flotation efficiency when the coarse porous stainless steel sparger (100 μm) was used in the laboratory column and when the variable gap sparger was used in the pilot column.

The organic loss from all column configurations (laboratory and pilot-scale) was less than 3%.

The scale up procedure was evaluated using data from the laboratory column and pilot column dimensions. Finally, using data from the laboratory column, industrial columns were designed.

Résumé

Le recyclage du papier est une pratique qui n'a cessé d'augmenter dans les dix dernières années en Amérique du Nord. La flottation est un procédé courant qui permet d'enlever l'encre des fibres (désencrage), ce qui était originalement accompli par des cellules méchaniques. Les colonnes de flottation sont une alternative aux cellules méchaniques. Pour ce project, des colonnes ouvertes et de Yang (une colonne remplie avec un réseau de chicanes metalliques) de laboratoire et pilote ont été utilisées afin de determiner leurs differents avantages: elles ont été également comparées aux circuits de cellules méchaniques.

Nous avons découvert que le type de générateur de bulles était important pour obtenir une meilleure flottation. Des générateurs de bulles en acier inoxydable qui produisent des petites bulles permettent une meilleure flottation, égale à celle des cellules méchaniques. Le réseau de chicanes metalliques est efficace pour augmenter le rendement de flottation lorsque les générateurs de bulles en acier inoxydable qui produisent des grosses bulles sont utilisés dans la colonne de laboratoire. Le réseau de chicanes metalliques est également efficace lorsque le générateur de bulles à ouverture variable fut utilisé dans la colonne pilote.

Les pertes organiques de toutes les différentes colonnes (de laboratoire et pilote) ont été de moins de 3%.

La procédure pour constuire des colonnes industrielles fut evaluée selon les données de la colonne de laboratoire et des dimensions de la colonne pilote. Finalement, les colonnes industrielle furent concues à partir des données de la colonne de laboratoire.

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Nomenclature

A_c column cross-sectional area

C_D drag coefficient

c_{ink} ink concentration

c_p particle concentration

d_b bubble diameter

d_c column diameter

d_p particle diameter

E flotation efficiency

E_A attachment efficiency

E_K collection efficiency

g gravitational acceleration

H_c collection zone height

H_f froth zone height

J superficial velocity (flowrate/column cross-sectional area)

k absorption coefficient

k_c rate constant

L organic loss

L_t length

N_d vessel dispersion number

P pressure

Q volumetric flowrate

R_c collection zone recovery

Re Reynolds number

R_{eq} equilibrium recovery

R_f froth zone recovery

R_{fc} overall flotation column recovery

R_∞ opaque pad reflectance

s	scattering coefficient
S_b	bubble surface area generation rate
t_i	induction time
t_s	contact time
U_{bt}	single bubble terminal velocity
U_{sg}	relative slip velocity
U_{sp}	particle slip velocity
w	basis weight
X_i	organic mass fraction
Y	yield
Y_i	ash mass fraction

Greek Letters

ε_g	gas holdup
ϕ	volume fraction
μ_f	fluid viscosity
ρ_p	particle density
ρ_{sl}	pulp density
τ_l	liquid retention time
τ_p	particle retention time

Chapter 1: Introduction

The degree of waste paper recycling in North America has been increasing steadily over the past few years. The 1990 US and Canadian recovery rates, defined as the amount of waste paper recovered for reuse compared with paper consumed, reached 33% and 25% respectively. Countries without forest reserves, such as Japan, have recovery rates as high as 50%. Another measure of the level of recycling is the amount of secondary fibre used in paper/board production compared with the total fibre used, also known as the utilization rate. Secondary fibre utilization is approximately 25% in the United States and about 10% in Canada. The utilization rate in Japan is considerably higher at 50% [1].

The main problem facing recycling mills is high waste paper transportation costs. As a result, most recycling facilities are located near urban centers. Other problems facing the recycling industry include finding a suitable deinking process, dealing with contaminants, and fighting a consumer opinion that recycled products are lower in quality [2]. Utilization rates of 50% are considered to be a practical maximum and as a result are the major limitations for mills. Significant losses of both fibre substance and strength occur during each recycle.

This chapter will focus on the flotation deinking of old newspapers (ONP) and old magazines (OMG) at Avenor's Gatineau paper recycling facility. The stages found in the deinking mill will be described. Finally, the flotation chemistry and possible flotation mechanisms will be discussed.

1.1 Deinking

Deinking is defined as any process which removes ink and other objectionable non-fibrous materials from a slurry of wastepaper [3]. Contaminants include all foreign elements such as rocks, sand, glass, and tramp metal. Glues, hot melts, and latexes are also contaminants and are generically called "stickies" [1]. "Stickies" are the result of book bindings, label backings, and adhesive coatings.

Avenor's Gatineau mill is an example of a recycling plant where newsprint, containing about 40% recycled fibres, is produced. The makeup of the newsprint consists of 59% thermomechanical pulp (TMP) and 1% kraft pulp. The deinking plant processes approximately 70% ONP and 30% OMG and has a capacity of approximately 500 t/d. The main stages in the deinking plant include: high-consistency pulping, coarse cleaning, flotation, fine cleaning, thickening, disperging, and bleaching [4]. A flowsheet of the deinking plant is shown in Appendix A.

1.1.1 High-Consistency Pulping

Pulping at Avenor, as with most deinking plants, is done on a batch basis. The main purpose of the pulping stage is to: 1) disperse the secondary fibre into a wet pulp slurry; 2) chemically and mechanically detach the ink particles from the fibres; and 3) maintain the integrity of contaminants, such as plastic and insoluble glues for later removal. Pulping is equivalent to liberation in mineral flotation. In mineral flotation the ore is crushed and ground into small particles in order to facilitate flotation or other separation techniques.

At this stage, the ONP and OMG are fed automatically to two high-consistency pulpers until a batch of 8 tonnes is reached. The pulpers mix the material at 15% consistency for 30 minutes. The chemicals (sodium hydroxide, fatty acid soap, hydrogen peroxide, and sodium silicate) required for downstream operations are also added to the pulpers. Figure 1.1 is a diagram of a high-consistency pulper.

The development of high-consistency pulpers has improved the performance of batch pulping systems. The advantages of high-consistency pulpers include [5]: 1) better ink separation and increased pulp brightness: 2) pulping time reduced to less than one hour per batch: and 3) lower power requirements by increasing the batch size for a given pulper.

1.1.2 Coarse Cleaning

In the coarse cleaning stage the accepts from the pulpers are passed through primary, secondary, and tertiary screens. The primary screen is a trash screen located at the outlet of the pulper which prevents large objects such as plastic bags, cans, and wire from continuing through the process. The secondary screens consist of high-density cleaners which remove staples, sand, and pieces of glass. Finally the tertiary 0.055" screens remove large ink particles, plastic, and pieces of glue. The rejects from this screening circuit report back to the primary coarse screen feed box.

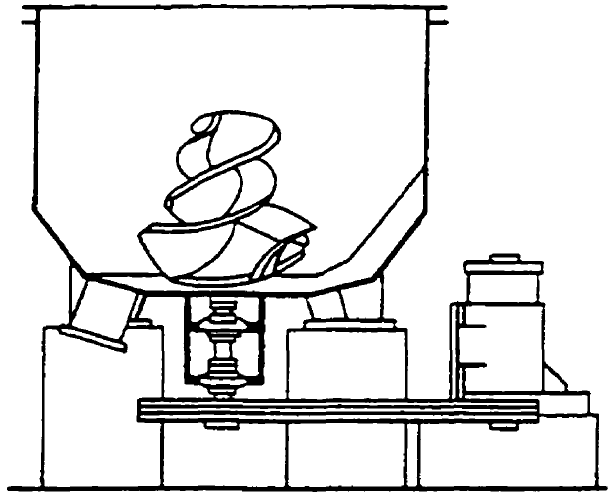

Fig. 1.1 Diagram of a high-consistency pulper [1].

1.1.3 Flotation

In the flotation process, the chemicals which were introduced in the pulpers cause the ink particles to flocculate and produce a foam. In a flotation cell the pulp slurry is aerated at low consistencies (percent solids). The ink and dirt particles become attached to the air bubbles, causing them to rise to the top of the cell and are removed as rejects. Flotation deinking can be divided into three stages [6]: 1) collision between the ink particle and the air bubble; 2) attachment between the ink particle and air bubble; and 3) flotation of the ink particle-bubble aggregate to the surface. Flotation chemistry and flotation mechanisms will be discussed in sections 1.2 and 1.3.

The flotation process at Avenor consists of two banks of six primary cells and two secondary cells (Figure 1.2). The rejects from the six primary cells are fed to the two secondary cells for further ink removal. The final rejects are sent for disposal and the accepts from the secondary cells are returned to the first primary cell.

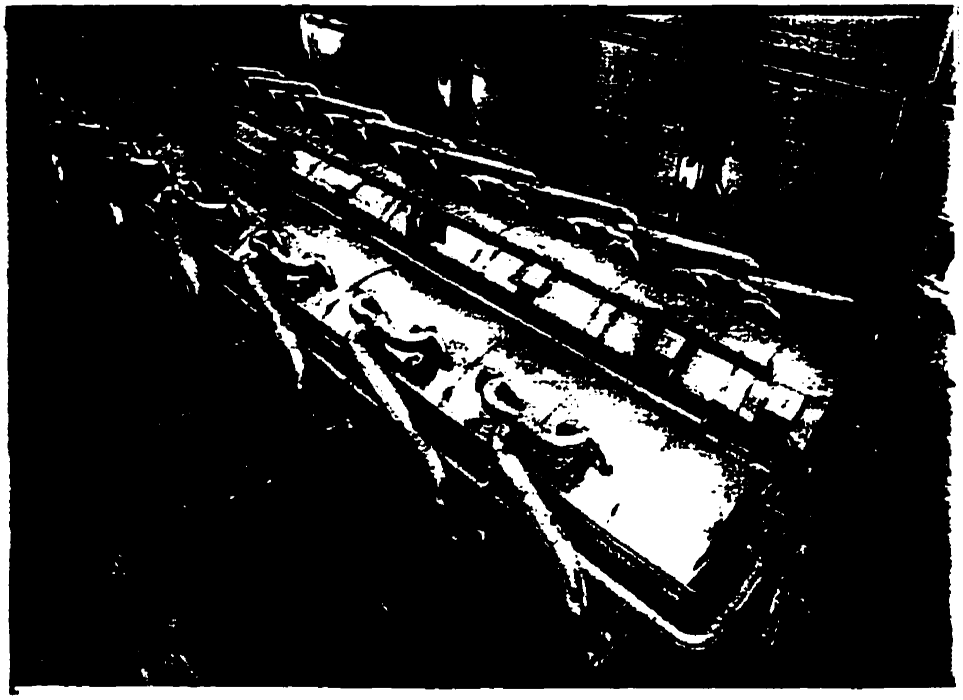

Fig. 1.2 Picture of Voith flotation cells at Avenor's Gatineau mill.

1.1.4 Fine Cleaning

Fine cleaning is a three step operation designed to maximize the cleaning efficiency at low pulp consistencies. The first stage consists of centrifugal lightweight cleaners. These cleaners separate the lighter contaminants such as glue, plastic, and light ink compounds according to density. The accepts are then treated with five stages of forward cleaners in order to remove sand. Finally, the accepts are passed through three stages of 0.008" fine screens.

1.1.5 Thickening

The pulp from the fine screens is thickened from 0.6% consistency to approximately 10% consistency using two disc filters. The pulp is then washed with water from the paper machine and fed through two twin wire presses. In the twin wire presses the pulp is washed with hot water and thickened to approximately 30% consistency. As a result of these operations, the dissolved solids in the pulp are removed. The water from the presses is sent for clarification and reused in the plant.

1.1.6 Disperging

The dispergers are used to refine and enhance the cleaned fibers at high temperature and high consistency. The dispergers break up any remaining ink particles so that they are essentially invisible. The dispergers are also used as mixers when hydrogen peroxide bleaching takes place.

1.1.7 Bleaching

Hydrogen peroxide bleaching takes place in the bleach tower. The retention time for the stock in the tower is approximately 45 minutes. The bleaching stage is used only if additional brightness is required. The stock is then diluted to about 10% consistency with recycled water from the paper machine and pumped to the high-density storage tank.

1.2 Flotation Chemistry

Chemistry is the key component in any flotation process. Most of the chemicals are added in the pulper in order to assist in the removal of the contaminants and to make them accessible for flotation. The chemicals added to the pulper at Avenor are: sodium hydroxide, hydrogen peroxide, sodium silicate, and a fatty acid soap. Calcium chloride is added to the flotation cells in order to improve ink particle collection (the function of calcium chloride will be discussed in the same section as the fatty acid soap). Clay is also important for flotation deinking. Due to its optical properties clay was found to improve flotation results [7,8]. Approximately 8-10% clay is required for flotation [9]. This amount of clay is supplied to the system by the OMG (30% of the feed) which contain 25-30% clay.

1.2.1 Sodium Hydroxide

Sodium hydroxide (NaOH), also known as caustic soda, is used to increase the pH to the alkaline region and to saponify or hydrolyze the ink resins. By raising the pH to 8-12 in the pulper, fibre swelling occurs which aids in ink removal and disintegration of paper into individual fibres [10]. During the swelling process, the fibres retain some water and become more flexible. When sodium hydroxide is added, "alkali darkening" occurs. Alkali darkening is a phenomena where the pulp fibres yellow and darken due to the high pH. Figure 1.3 shows the results of alkali darkening on a 70:30 ONP/OMG furnish when only caustic soda was added. A decrease in brightness can be observed after a pH of approximately 10.25.

1.2.2 Hydrogen Peroxide

Hydrogen peroxide (H_2O_2) is used to prevent alkali darkening in the pulper. The peroxide reacts with caustic soda as follows:

$$H_2O_2 + NaOH \leftrightarrow HOO^- + Na^+ + H_2O \qquad (1.1)$$

where pH = 10.0 to 11.5 and temperature = 40 to 80°C. The active bleaching agent in reaction 1 is the perhydroxyl anion (HOO^-).

In order to maximize the amount of perhydroxyl anion the side reactions which decompose peroxide must be reduced [11]. The side reactions are shown by reaction 1.2:

$$M^{2+} + H_2O_2 \rightarrow \frac{1}{2} O_2 + H_2O \qquad (1.2)$$

where M represents heavy metal ions such as manganese, copper, and iron. The metals are found in the waste paper or in the mill water. Enzymes like catalase and high pH and temperature promote the decomposition reaction.

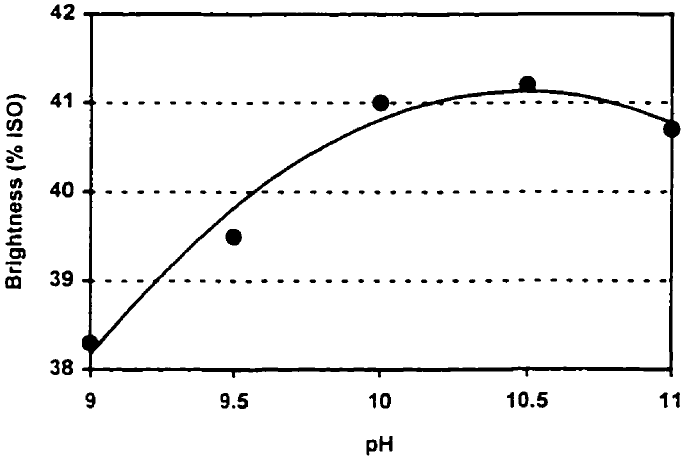

Fig. 1.3 Effect of pH on pulper brightness; 70:30 ONP/OMG furnish [11].

1.2.3 Sodium Silicate

Sodium silicate (Na_2SiO_3) is a multi-purpose reagent. Silicate performs three operations, namely: 1) peroxide stabilizer; 2) acts as a dispersant to prevent ink from redepositing on the fiber surface; and 3) source of alkalinity and pH buffer. Silicate acts as a peroxide stabilizer since it is believed to form a colloidal structure with the heavy

metal ions. Silicate is a source of alkalinity according to the reaction with water as shown below:

$$Na_2SiO_3 + H_2O \leftrightarrow 2Na^+ + OH^- + HSiO_3^- \quad (1.3)$$

1.2.4 Fatty Acid Soap

Fatty acid soaps, as shown in Figure 1.4, are a type of surfactant. The sodium soap is usually a blend of acids with 16 to 18 carbon atoms, such as stearic and oleic acids [12]. At Avenor, the soap is supplied in liquid form and must be converted to the calcium soap before it can function as a collector. A source of calcium ions must be introduced into the system in order to form the calcium salt of the fatty acid. Calcium ions are present in the magazine coatings as calcium carbonate and are added to the flotation cells as calcium chloride. In the flotation cell the water hardness must be at least 200 ppm calcium.

1.3 Flotation Mechanisms

In the process of flotation deinking, the ink particles must attach themselves to the air bubbles rising through the furnish. For flotation to be effective, the size of the ink particles must be maintained within an optimum range (10-100 μm). If the ink particles are too small they will not be collected efficiently due to the low probability of encountering an air bubble. When the ink particles are too large, low collection efficiencies are also observed due to reduced attachment efficiencies [13,14]. Figure 1.5 illustrates the general operating principle in flotation deinking.

In flotation deinking, surfactants (fatty acid soaps) are used as collectors. The oil based printing inks used in magazines and newspapers are naturally hydrophobic. When the anionic surfactant is absorbed onto the ink particles, the hydrophilic part of the surfactant is oriented into the water. The same situation is believed to occur at the air bubbles, that is, the surfactant's hydrophilic part orients into the water and the

hydrophobic part aligns itself with the hydrophobic air bubble. The ink particles become hydrophilic and are dispersed in water. Larssen et al [15,16] and Putz et al [17] have proposed two different models for bubble-particle attachment in the presence of calcium ions.

Larssen et al proposed that calcium soap precipitates onto the ink particles. This produces a coating of small soap flakes on the ink particles allowing agglomeration to occur. Once agglomerated, the ink particles are large enough for rapid attachment to air bubbles. Putz et al proposed that the calcium ions bridge the hydrophilic groups of the ink particles and air bubbles together making particle collection possible. Regardless of the particle-bubble attachment mechanism, calcium ions play a vital role.

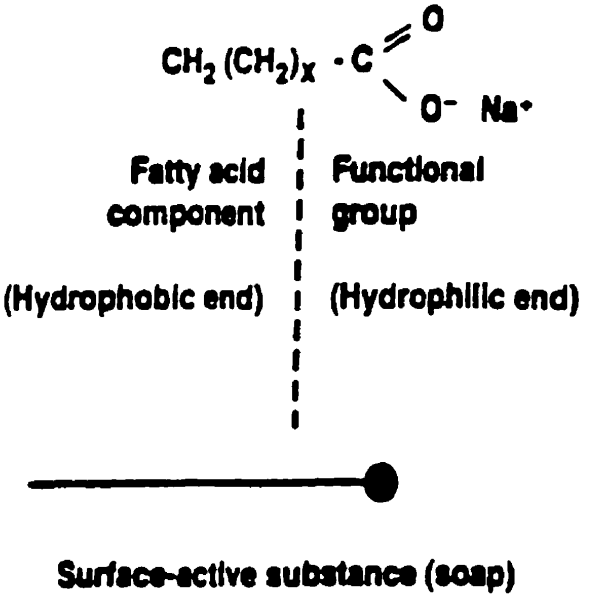

Fig. 1.4 Chemical composition of fatty acid soaps [12].

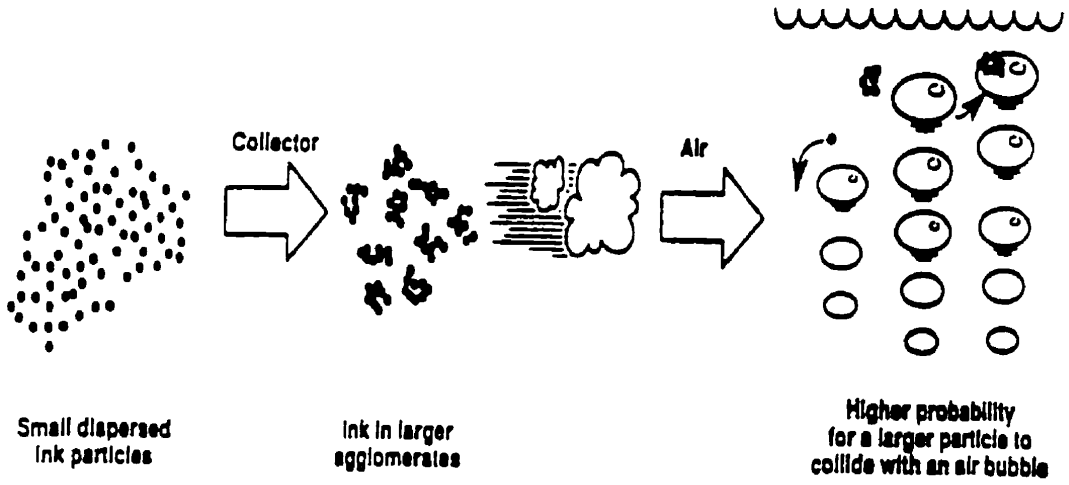

Fig. 1.5 Basic operating principle of flotation deinking [13].

1.4 Project Objectives

The general objective of this project is to run laboratory and pilot-scale tests to establish the relative merits of open and packed column flotation in the deinking of wastepaper. and to compare these forms of column flotation against mechanical cell flotation. Avenor's Gatineau mill was the site of all experiments. This general objective will be met through the completion of the following tasks:

1) Selection of operating conditions for open and packed columns.

2) Assessment of column performance over long term operation.

3) Evaluation of scale up procedures.

Chapter 2: Theoretical Principles

2.1 Nomenclature

Flotation is traditionally performed using banks of mechanical cells. Column flotation consists of tall vertical reactors where gas bubbles are generated with spargers at the bottom and wash water is added at the top. The main advantages of columns include improved separation performance, low capital and operational costs, low floor space requirements, and adaptability to automated control [18]. Many different types of column cell configurations exist, however only the open and packed cells will be discussed. All terms and definitions are referenced from Finch and Dobby [14] (unless otherwise specified).

2.1.1 Open Column

The conventional, or open flotation column, is illustrated in Figure 2.1. In column flotation rising gas bubbles interact with the descending pulp in the collection zone (H_c). Gas bubbles are normally generated with internal spargers, such as porous stainless steel pipes or variable gap spargers.

Wash water is added in order to stabilize the froth. Wash water replaces the water which is naturally drained from the froth. The remainder of the wash water flows through the froth and cleans the froth of particles entrained in the water crossing with the bubbles from the collection zone. Therefore, the froth zone is also called the cleaning zone (H_f). The flow of water moving through the froth is called the bias water, a positive value

corresponding to a net flow downwards. For efficient cleaning of entrained particles bias rate must be positive.

The overflow is rich in the floatable (hydrophobic) material, which often forms the concentrate in mineral systems. The unfloatable (hydrophilic) material is collected as underflow from the bottom of the column. Deinking is a reverse flotation process where the valuable material (the accepts) is the underflow and the overflow is the waste material (the rejects).

The flowrates of the different streams in the column are normally expressed as superficial velocities (or rates). Superficial velocity is the volumetric flowrate of a particular steam divided by the column cross sectional area:

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

where i can be gas (G), feed (F), wash water (W), bias (B), rejects (R), or accepts (A). Superficial velocities are useful for comparing columns of different diameters and are usually expressed in cm/s.

2.1.2 Packed Column

A packed column incorporates stacks of corrugated stainless steel plates inside an open column (Figure 2.2). The packing plates are arranged in blocks positioned at right angles to each other. A packed column is operated in the same manner as an open column and the terms are identical.

The reported technical advantages of packed columns are [19]: 1) provision of small tortuous flow passages for intimate particle-bubble contact; 2) allowance for efficient water washing through an almost unlimited froth depth; 3) elimination of the need for spargers since the packing elements break up the air into bubbles; and 4) damping of axial mixing.

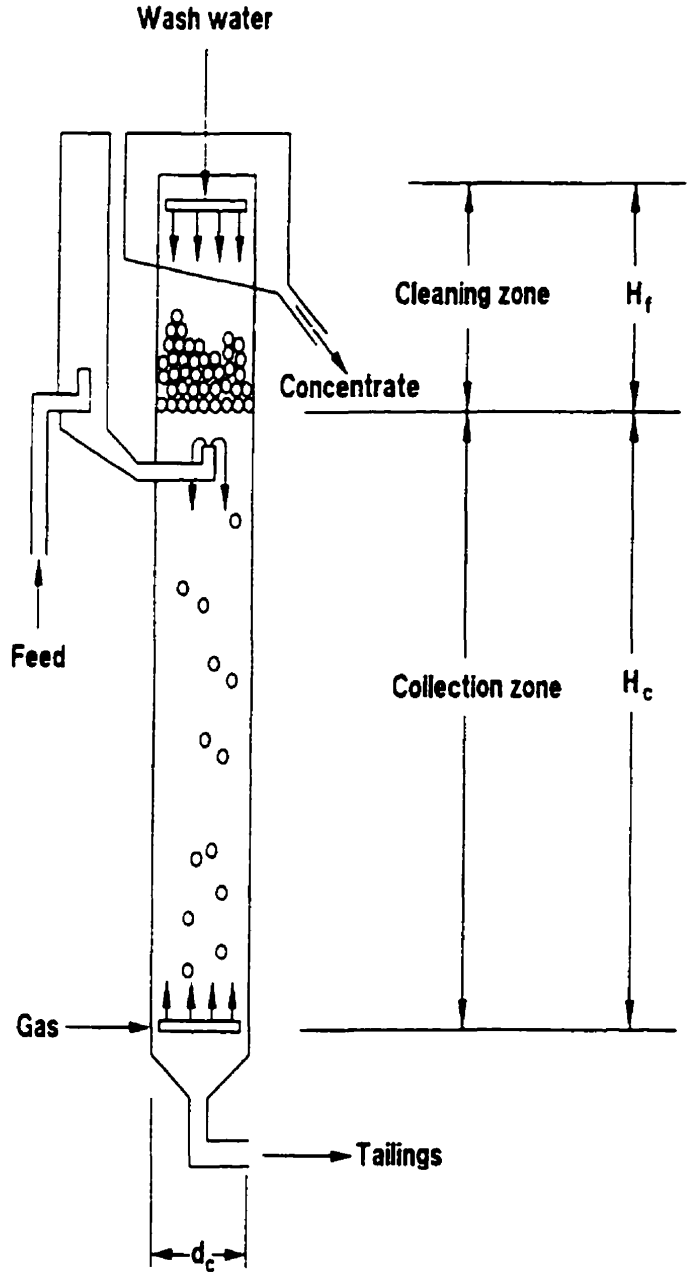

Fig. 2.1 Schematic diagram of an open column. From Finch and Dobby [14].

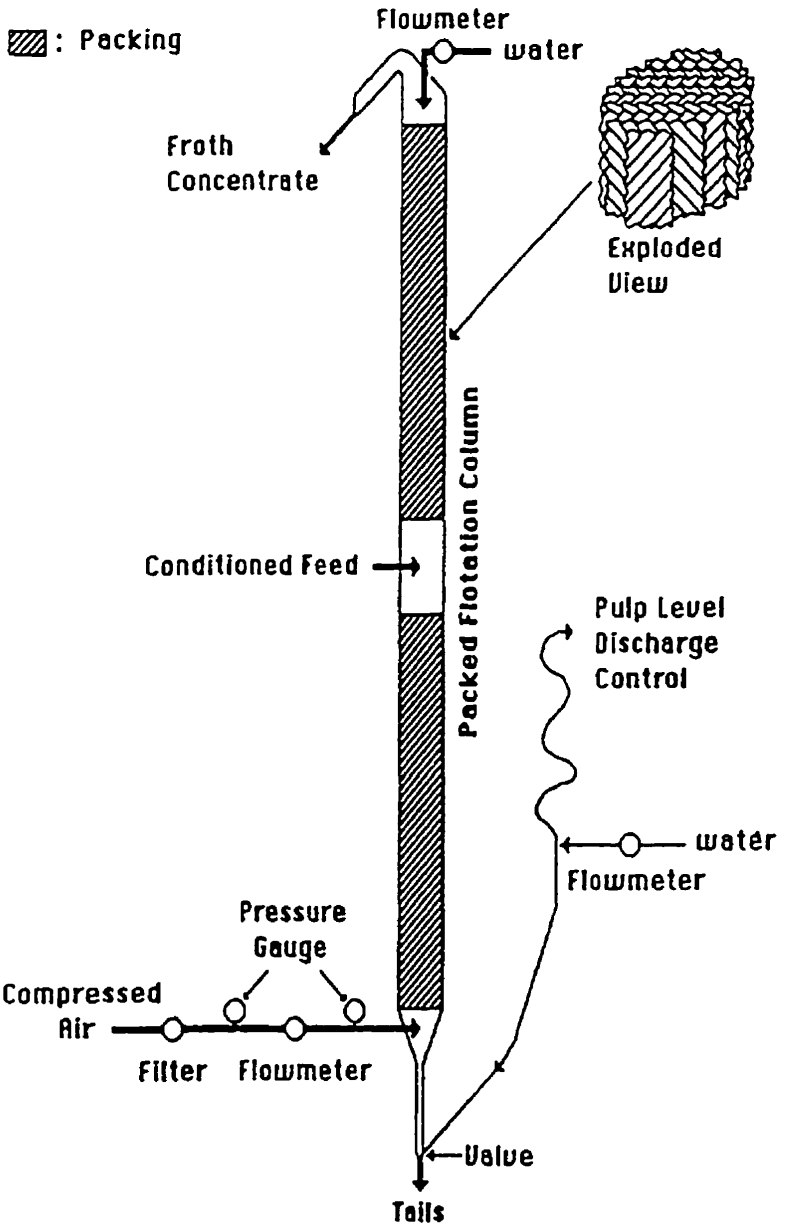

Fig. 2.2 Schematic of packed column. From Yang et al [19].

2.2 Collection Zone

2.2.1 Gas Holdup

When air is injected into a column, pulp is displaced. The volume fraction of gas (air bubbles) is defined as the gas holdup (ε_g). Gas holdup is useful in determining the flow regime in the collection zone (discussed in section 2.2.2) and is essential for estimating bubble size (section 2.2.3.1), bubble surface area rate (section 2.2.3.2), and pulp retention time. Local gas holdup measurements can be used to determine axial variations in gas holdup along the column.

The pressure difference method can be used to measure local gas holdup in a column. In this method, the local section is defined by the distance between the pressure tapping points. In order to calculate the gas holdup using the pressure difference method, it is assumed that the dynamic component of the pressure and the bubble-particle aggregate density are negligible. The pressure at A and B (Figure 2.3) is given by:

$$P_A = \rho_{sl}\, g\, L_A (1-\varepsilon_{gA}) \qquad (2.1a)$$

$$P_B = \rho_{sl}\, g\, L_B (1-\varepsilon_{gB}) \qquad (2.1b)$$

where ρ_{sl} is the pulp density, and ε_{gA} and ε_{gB} are the gas holdup above A and B respectively. The pressure difference between A and B (ΔP) is:

$$\Delta P = \rho_{sl}\, g\, \Delta L (1-\varepsilon_g) \qquad (2.2)$$

where ε_g is the gas holdup between A and B and is given by:

$$\varepsilon_g = 1 - \frac{\Delta P}{\rho_{sl} g \Delta L} \qquad (2.3)$$

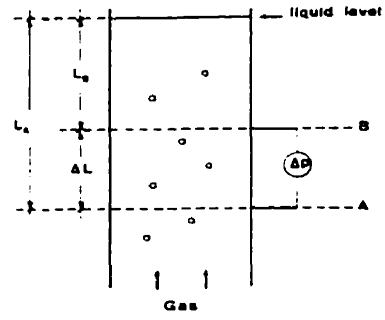

Fig. 2.3 Pressure difference method for measuring gas holdup [14].

2.2.2 Flow Regime

The flow regime in the collection zone can be determined from the relationship between ε_g and J_g (Figure 2.4). Gas holdup increases approximately linearly and then deviates at some J_g. The linear section is characterized by a homogeneous distribution of bubbles of uniform size rising at a uniform rate and is called the bubbly flow regime. Above the transition J_g the flow regime becomes churn-turbulent. Churn-turbulent flow is characterized by large bubbles rising rapidly, displacing water and small bubbles downward.

Normally, columns are operated in the bubbly flow regime. Therefore, there is an upper constraint on the gas rate. Level control and gas holdup measurement become difficult in the churn-turbulent regime.

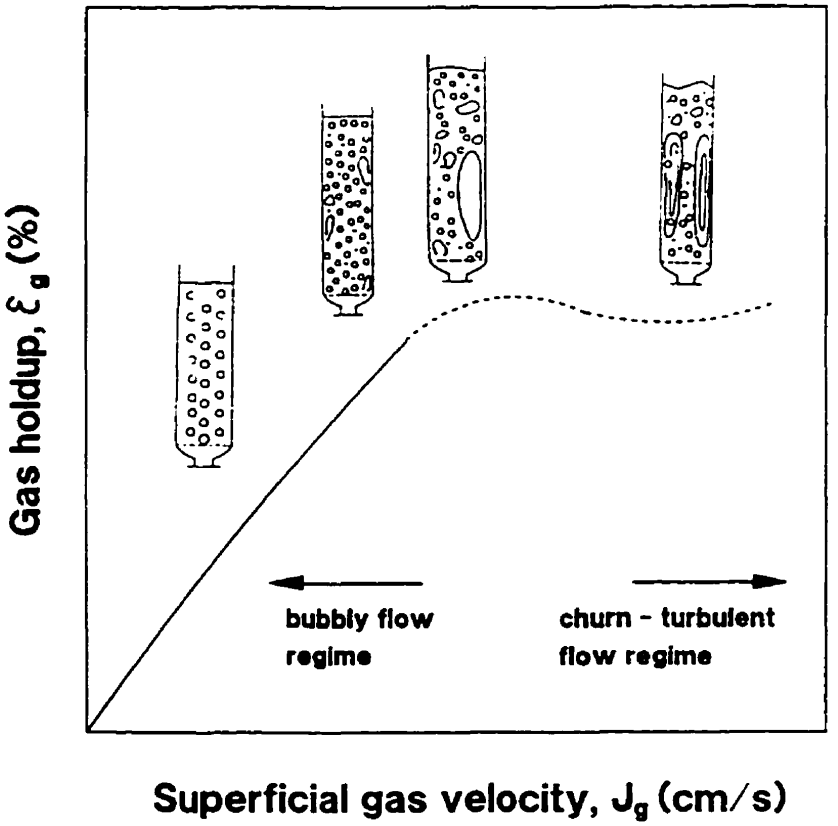

Fig. 2.4 Gas holdup as a function of gas rate [14].

2.2.3 Bubbly Flow Model

The bubbly flow model, also referred to as the drift flux model [20], can be used to infer otherwise difficult to obtain information, e.g. bubble size and bubble surface area rate, from readily measured data such as ε_g, J_g, and J_l. The slip velocity is the velocity of one phase relative to another. In column flotation the relative slip velocity (U_{Sg}) between the gas phase and the liquid phase is defined as:

$$U_{Sg} = \frac{J_g}{\varepsilon_g} + \frac{J_l}{1-\varepsilon_g} \tag{2.4}$$

The slip velocity is also given by:

$$U_{Sg} = U_{bT}(1 - \varepsilon_g)^{m-1} \tag{2.5}$$

where U_{bT} is the single bubble terminal velocity [21]. For most cases m is 3. Therefore equation 2.5 becomes:

$$U_{Sg} = U_{bT}(1 - \varepsilon_g)^2 \tag{2.6}$$

Results for single bubbles in air-water systems are presented in Figure 2.5. An approximation of the relationship between U_{bT} and bubble diameter (d_b) for contaminated systems is given by Karamanev et al [22]:

$$U_{bT} = \sqrt{\frac{4gd_b}{3C_D}} \tag{2.7}$$

where C_D is the drag coefficient of the gas bubbles and is given by [23]:

$$C_D = \frac{24(1 + 0.173\,Re^{0.657})}{Re} + \frac{0.413}{1 + 16300\,Re^{-1.09}} \tag{2.8}$$

For light rigid spheres rising in a Newtonian liquid with Re greater than 130 (bubbles in water) C_D is approximately 0.95. Therefore, equation 2.7 becomes:

$$U_{bT} = \sqrt{1.4gd_b} \tag{2.9}$$

Equation 2.9 is included on Figure 2.5.

2.2.3.1 Bubble Size Estimation

Bubble size can be measured accurately by photography. However, this method is time consuming and can only be applied to transparent columns. Using the bubbly flow model bubble size can be estimated. By equating equations 2.4 and 2.6, a relationship for U_{bT} can be obtained:

$$U_{bT}(1-\varepsilon_g)^2 = \frac{J_g}{\varepsilon_g} + \frac{J_l}{1-\varepsilon_g} \qquad (2.10)$$

Therefore, if ε_g, J_g, and J_l are known U_{bT} can be calculated. Finally, using eq. 2.9, d_b can be estimated.

2.2.3.2 Bubble Surface Area Generation Rate

The surface area generation rate of bubbles S_b ($(cm^2$ bubble area/s)/(cm^2 column area) or s^{-1}) is the variable which controls solids removal rate (or carrying rate). Bubble surface area generation rate is given by:

$$S_b = \frac{6J_g}{d_b} \qquad (2.11)$$

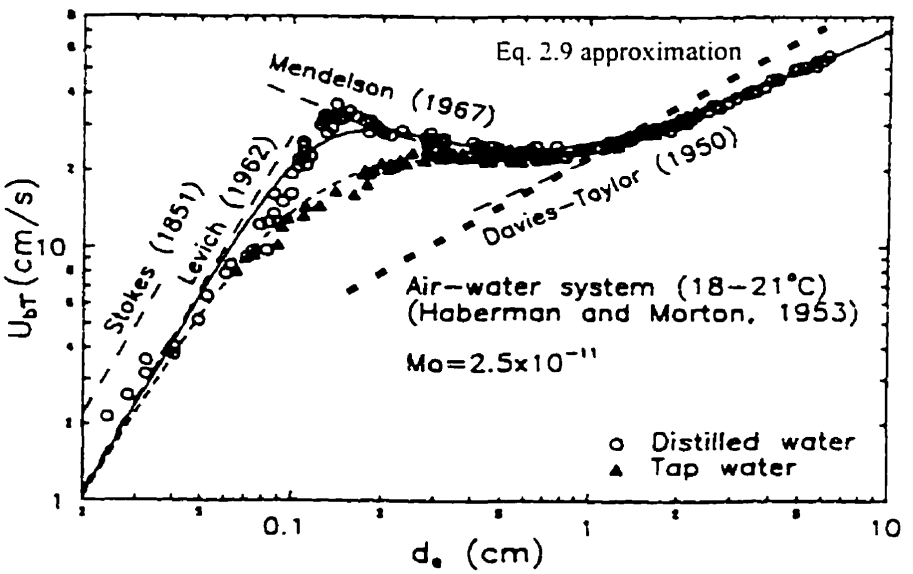

Fig. 2.5 Classical U_{bT} versus d_b results in an air-water system [21]: Upper curve is water only; lower curve is for "contaminated" water, e.g. water with surfactant.

2.2.4 Particle Collection

In flotation deinking, particles can be collected by one of three mechanisms: 1) particle-bubble collision followed by attachment due to the hydrophobic nature of the particle surface; 2) entrainment of the particle within the boundary layer and wake of the bubble; and 3) entrapment of bubbles. The first mechanism is selective and is important for ink collection. Depending on water hardness, this mechanism is also responsible for removing fibres [24]. The entrainment mechanism is not selective. Large bubbles tend to carry less water per unit gas volume across the froth/pulp interface than small bubbles. Therefore fibre loss by entrainment will be lower when larger bubbles are generated [25]. The third mechanism is another method for fibre loss [26]. Fibres can form networks or flocs while in suspension and small bubbles can become trapped. As a result the bulk density of the fibre network is reduced and the fibres are carried to the froth.

Only the first mechanism for particle collection will be discussed in detail. The collection efficiency (E_K) is defined as the fraction of particles swept out by a bubble that collide with, attach to, and remain attached to the bubble. The rate of particle removal is given by:

$$\frac{dc_p}{dt} = \frac{1.5 J_g E_K c_p}{d_b} \tag{2.12}$$

where c_p is the concentration of particles. This is equivalent to the first-order rate process with rate constant k_c given by:

$$k_c = \frac{1.5 J_g E_K}{d_b} \tag{2.13}$$

The collection zone in laboratory-scale columns (large H_c/d_c ratios) tend to exhibit plug flow transport conditions. For a first-order rate process with plug flow transport the recovery of particles in the collection zone (R_c) is given by:

$$R_c = R_{eq}[1 - \exp(-k_c \tau_p)] \tag{2.14}$$

where τ_p is the particle retention time and R_{eq} is the equilibrium recovery at long flotation times. For non plug flow conditions (industrial-scale columns) equation 2.14 must be modified to account for short circuiting of particles (section 2.2.5).

Collection efficiency can be expressed in terms of collision efficiency (E_C) and attachment efficiency (E_A) according to:

$$E_K = E_C E_A \tag{2.15}$$

Collision efficiency is the fraction of all particles swept out by the projected area of the bubble that collide with the bubble. Hydrodynamic drag tends to sweep the particle around the bubble, following the fluid streamlines and the particle will slide along the bubble surface for a period of time called the contact time (t_s). Attachment efficiency is the fraction of all colliding particles that undergo successful attachment during the time of contact. Attachment occurs when the intervening liquid (disjoining) film between the particle and the bubble thins, ruptures, and a three phase (solid-liquid-air) contact line forms. The time for this to occur is the induction time (t_i). Attachment will occur when the contact time is greater than the induction time. Particle detachment is not considered since detachment is minimal for the small particles encountered in flotation deinking (<100 μm).

2.2.5 Mixing

Laboratory-scale columns with large H_c/d_c ratios exhibit plug flow conditions. The recovery in the collection zone for a first-order rate process with plug flow transport is given by equation 2.14. The recovery for particles in a system exhibiting perfect mixing is given by [27]:

$$R_c = R_{eq}[1 - (1 + k_c\tau_p)^{-1}] \tag{2.16}$$

where k_c, τ_p, and R_{eq} are the same as in Eq. 2.14. Mixing has a detrimental effect on recovery since particles are short circuited and have reduced probability of encountering to air bubbles. The liquids and solids in industrial-scale columns are transported under conditions between those of plug flow and perfectly mixed flow. The plug flow

dispersion model can be used to describe the axial mixing process in the collection zone. The effect of mixing on recovery is given by the following equation:

$$R = R_{eq}\left[1 - \frac{4a\exp(\frac{1}{2N_d})}{(1+a)^2\exp(\frac{a}{2N_d}) - (1-a)^2\exp(\frac{-a}{2N_d})}\right] \quad (2.17)$$

where

$$a = (1 + 4k\tau N_d)^{1/2}$$

and N_d is the vessel dispersion number given by:

$$N_d = \frac{0.063 d_c (J_g / 1.6)^{0.3}}{[(J_{sl}/(1-\varepsilon_g)) + U_{sp}]H_c} \quad (2.18)$$

where U_{sp} is the particle slip velocity and can be obtained from the following equation:

$$U_{sp} = \frac{g d_p (\rho_p - \rho_{sl})(1-\phi_s)^{2.7}}{18\mu_f(1 + 0.15 Re_p^{0.687})} \quad (2.19)$$

where

$$Re_p = \frac{d_p U_{sp} \rho_l (1-\phi_s)}{\mu_f} \quad (2.20)$$

The particle mean retention time (τ_p) can be estimated according to:

$$\tau_p = \frac{\tau_l (J_{sl}/(1-\varepsilon_g))}{J_{sl}/(1-\varepsilon_g) + U_{sp}} \quad (2.21)$$

where τ_l is the liquid retention time and is defined as:

$$\tau_l = \frac{H_c(1-\varepsilon_g)}{J_{sl}} \quad (2.22)$$

2.3 Froth Zone

One of the advantages of column flotation is the ability to add wash water to the froth. Wash water provides the bias water and the water necessary to overflow the collected solids into the launder. The bias water replaces the water naturally drained from the froth. As a result, bias water tends to promote froth stability. Wash water decreases the gas holdup in the froth by increasing the water content. The froth zone consists of

three zones (Figure 2.6): 1) an expanded bubble bed; 2) a packed bubble bed; and 3) a conventional draining froth above the wash water inlet.

Bubbles from the collection zone enter the expanded bubble bed after colliding with the first layer of bubbles which define a distinct interface. Upon entry to the froth, the bubbles remain spherical, small, and are relatively homogeneous. Bubble coalescence in this region may be caused by the shock pressure waves generated as bubbles from the collection zone collide with the interface. The liquid content ($1-\varepsilon_g$) in the expanded bubble bed is generally greater than 25%.

The next zone in the froth is the packed bubble bed region and extends to the wash water inlet level. In this zone the bubbles are relatively spherical but range in size. In this region the liquid content is less than 25%. The flow of bubbles upwards, at least in a laboratory column, is close to plug flow provided the wash water is well distributed. The rate of coalescence is lower in the packed bed region than in the expanded bed region. Coalescence in this region is due to collisions caused by the larger bubbles which are rising faster.

Depending on the wash water distributor position, the conventional draining froth zone may not exist. In some applications, the wash water distributors are placed above the froth and a drained froth region does not form. The main purpose of this region is to convert vertical into horizontal motion to recover the solids. A disadvantage associated with submerging the distributor into the froth is that solid accumulation may occur. However, more wash water will be split to the bias the deeper the distributor is submerged.

Cleaning in the froth zone (also referred to as cleaning zone) is defined as the removal of particles which are recovered by entrainment in the water. All particles (hydrophobic and hydrophilic) are subject to entrainment. Entrained particle recovery has been found to be proportional to feed water recovery. The variables which affect the recovery of entrained particles are the gas rate, bias rate, and froth depth. As J_g increases the concentration of feed water in the froth increases. A high J_g tends to have detrimental

effects on water recovery. It is difficult to compensate entrainment with wash water if the J_z becomes too high. Often deep froths (~ 100 cm) are more advantageous than shallow ones. Deep froths accommodate surges in level and dampen down the entrainment caused by high gas rates.

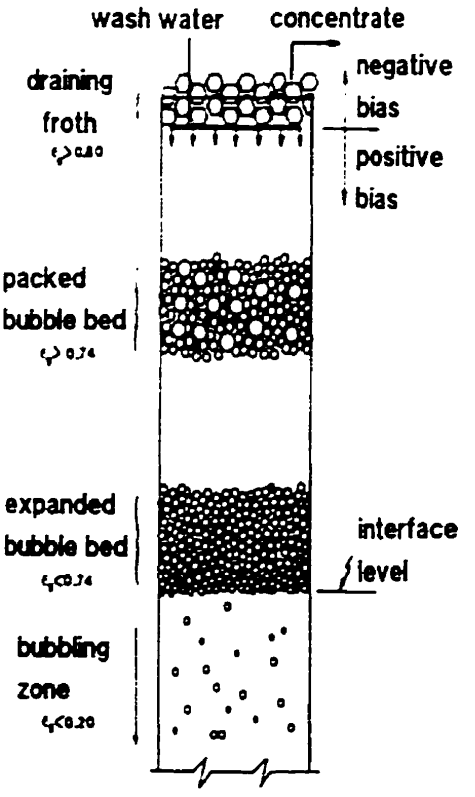

Fig. 2.6 Diagram of froth structure [14].

At the interface between the collection zone and the froth zone particle transport occurs in both directions. Particles are transported from the collection zone to the froth zone by attachment to rising bubbles. A portion of the particles within the froth are dislodged from the bubbles as a result of coalescence and are transported from the froth zone back to the collection zone by the bias water. This phenomena is referred to as froth drop back. The complement to froth drop back is froth zone recovery (R_f). The interaction between the two zones is shown schematically in Figure 2.7.

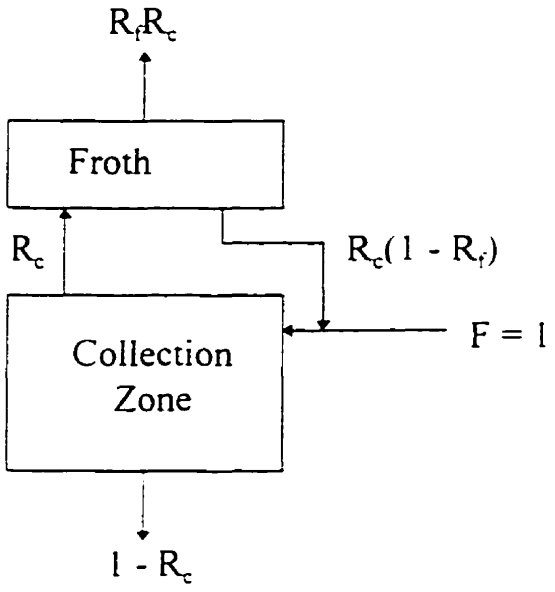

Fig. 2.7 Conceptual configuration of collection and froth zones.

The overall flotation column recovery (R_{fc}) is defined as:

$$R_{fc} = \frac{R_c R_f}{R_c R_f + 1 - R_c} \tag{2.23}$$

There is limited data for R_f. It is believed that R_f in laboratory/pilot columns is between 40 and 80%. In larger diameter columns R_f can be considerably lower.

2.4 Column Scale Up

Column scale up involves specifying a target recovery and a required throughput. Column geometry is then determined using the governing equations. Laboratory or pilot-scale columns are used to collect scaling up data and also to perform amenability testing. Amenability testing determines whether column cells are suited to the task.

Using the laboratory-scale column overall recovery and retention time data can be collected. Using equation 2.14 (collection zone recovery for a first-order rate process with plug flow transport) the overall collection rate constant can be determined. Overall rate constants can be equated to collection zone rate constants assuming perfect froth

zone recovery. This assumption is valid in small diameter columns due to the stability of the froth provided by the walls.

Once the collection rate constant has been determined the mixing regime and retention time in the target column can be estimated using the equations for the plug flow dispersion model as discussed in section 2.2.5. The target recovery is an overall recovery but the recovery used in equation 2.17 is the collection zone recovery. Therefore, the target recovery must be converted to R_c using equation 2.23 after assuming a value for R_f (typically 0.5) [28]. Perfect froth zone recovery cannot be assumed for large diameter columns since significant froth dropback occurs.

All variables (i.e. fluid viscosity and particle diameter) and operating conditions (i.e. J_g and ε_g) are specified or assumed and the equations for the plug flow dispersion model are solved by iteration.

2.5 Analytical Techniques

2.5.1 Effective Residual Ink Concentration

Effective residual ink concentration (ERIC) is a useful method for determining the amount of ink on a pad [29]. The relationship relating the reflectance of an opaque pad of paper (R_∞) measured at a wavelength of 950 nm to the amount of ink in the paper is given by:

$$f(R_\infty) = \frac{(1 - R_\infty)^2}{2R_\infty} \tag{2.24}$$

Equation 2.24 can also be expressed as:

$$f(R_\infty) = \frac{k}{s} \tag{2.25}$$

where k is an absorption coefficient and s is a scattering coefficient. Absorption and scattering coefficients of recycled newsprint are averages of its components (paper and ink), weighted by their concentrations (c). Therefore the coefficients become:

$$k_{rec} = (1 - c_{ink})\, k_{pap} + c_{ink} k_{ink} \tag{2.26}$$

$$s_{rec} = (1 - c_{ink})\, s_{pap} + c_{ink} s_{ink} \tag{2.27}$$

where rec and pap stand for recycled newspaper and paper, respectively. Ink concentrations are very small, therefore $(1-c_{ink})$ tends to unity. The term k_{ink} is much greater than k_{pap}. As a result the product $c_{ink}k_{ink}$ contributes significantly to k_{rec}. The product of $c_{ink}s_{ink}$ does not contribute to s_{rec} since the term s_{ink} is not significant. Therefore, equations 2.26 and 2.27 become:

$$k_{rec} = k_{pap} + c_{ink}k_{ink} \tag{2.26b}$$

$$s_{rec} = s_{pap} \tag{2.27b}$$

The scattering coefficient of a sheet with known basis weight (w) can be found by measuring its reflectance over a black backing (R_0) and the reflectance of an opaque pad of the same paper (R_∞) according to:

$$s = \frac{1}{w\left(\frac{1}{R_\infty} - R_\infty\right)} \ln\left[\frac{1 - R_0 R_\infty}{1 - \frac{R_0}{R_\infty}}\right] \tag{2.28}$$

The absorption coefficient for any sample can be determined by relating equations 2.24 and 2.25 and multiplying both sides by the scattering coefficient:

$$s\frac{k}{s} = s\frac{(1 - R_\infty)^2}{2R_\infty} \tag{2.29}$$

where s can be determined using equation 2.27 or 2.28 when s_{pap} is known. For recycled newspaper, the k in equation 2.29 is equal to k_{rec} in equation 2.26b. Therefore, the effective residual ink concentration (c_{ink}) can be determined from equation 2.26b provided k_{ink} and k_{pap} are known.

2.5.1.1 Flotation Efficiency

Flotation efficiency (E) is used to measure deinking performance. Flotation efficiency in this thesis is defined as:

$$E = \frac{c_i - c_f}{c_i} \tag{2.30}$$

where c is the concentration of ink and the subscripts are for initial (i) and final (f).

2.5.1.2 Ink Recovery

Ink recovery (R) is defined as:

$$R = \frac{[c_i S_i Q_i \rho_i] - [c_f S_f Q_f \rho_f]}{c_i S_i Q_i \rho_i} \tag{2.31}$$

where S, Q, and ρ represent consistency, volumetric flowrate, and stream density.

2.5.2 Mass Balance

The overall mass balance of the column is a balance between the flowrates of the different streams: feed (F), wash water (W), accepts (A), and rejects (R). The mass balance can be expressed as follows:

$$F + W = A + R \tag{2.32}$$

The main components of each stream are: water, organics, and ash. Organics consist of fibres, oils, and other materials which are combustible at 575°C. Ink is a component of each stream, however it can be assumed that its mass is negligible [30]. The water balance can be expressed as:

$$F\,\rho_F\,(1 - X_F - Y_F) + W = A\,\rho_A\,(1 - X_A - Y_A) + R\,\rho_R\,(1 - X_R - Y_R) \tag{2.33}$$

where X_i and Y_i are the mass fractions of organics and ash in their respective streams, where i = F, W, A, and R. In addition, ρ_i is the density of each stream and is given by:

$$\rho_i = \frac{1}{\left(\frac{1 - X_i - Y_i}{1}\right) + \frac{X_i}{\rho_{fibres}} + \frac{Y_i}{\rho_{ash}}} \tag{2.34}$$

where ρ_i is expressed in g/cm^3. The organic and ash balances can be expressed as:

$$F\,\rho_F\,X_F = A\,\rho_A\,X_A + R\,\rho_R\,X_R \tag{2.35}$$

$$F\,\rho_F\,Y_F = A\,\rho_A\,Y_A + R\,\rho_R\,Y_R \tag{2.36}$$

2.5.2.1 Organic Loss

Organic loss (L) is another method for assessing column performance. Organic loss represents the hydrophilic material (primarily fibres) which is recovered to the rejects by entrainment. Organic loss is calculated according to the following equation:

$$L = \frac{R\rho_R X_R}{F\rho_F X_F} \tag{2.37}$$

2.5.2.2 Yield

Yield (Y) is used to determine throughput. Yield is the complement of organic loss and is given by:

$$Y = 1-L \tag{2.38}$$

Data for the mass balance was reconciled using NORBAL3 [31]. Data reconciliation is necessary due to the uncertainty (quantified by the standard deviation) associated with experimental data. The pulp feed consists of low percent solids (~ 1%) and the slurry densities of all streams is approximately 1 g/cm^3. Therefore, data reconciliation was only performed on the pulp flowrates. The pulp flowrates have the greatest effect on the mass balance since they have significant magnitudes and standard deviations.

Chapter 3: Experimental

3.1 Approach

Deinking experiments were performed at Avenor using open and packed laboratory and pilot-scale flotation columns. The columns were fed continuously with pulp from the feed end of the plant flotation cells. Various operating conditions were altered in the columns, namely: gas rate, retention time, froth depth, and bias rate. In the laboratory column, these parameters were studied for two porous stainless steel spargers (nominal pore diameters of 0.5 and 100 μm) and no sparger (in the case of packing). The operating conditions in the pilot column were investigated using an industrial variable gap sparger [32]. Deinking experiments were compared according to flotation efficiency and organic loss.

The laboratory-scale columns (open and packed) were used to select the operating conditions required depending on sparger type. Once the conditions were determined, the performance (flotation efficiency and organic loss) of both columns were compared to each other and to the mechanical cells. The pilot-scale columns (open and packed) were used to verify the scale up of the laboratory columns. The pilot columns were also used to assess long term operation and to make a further comparison to the mechanical cells.

3.2 Apparatus

3.2.1 Laboratory-Scale Column

The laboratory-scale columns (0.102 m in diameter and 4.65 m high) were fully automated (Figure 3.1). Figure 3.1 is a diagram of the open column; the packed column had the same instrumentation and is identical except for the packing material placed inside. Four pressure transmitters (Bailey, model PTSDDD122B2100) were installed along the length of the columns in order to measure the gas holdup profile and froth depth. Three peristaltic pumps (Masterflex, model 7529-20), equipped with I/O cards, were used to control the flow of feed, accepts, and wash water. The rate of feed and accepts was measured with magnetic flowmeters (Fisher & Porter, model 10D1475PN07PL29). The gas rate was controlled with the aid of a mass flowmeter and controller (MKS, model 1162B-30000SV). Compressed air for the air flowmeter was supplied at 80 psi from the plant and was reduced to 50 psi using a regulator. The pressure transmitters, pumps, and flowmeters were controlled or monitored using a serial I/O (Transduction, model OPTO1) and a computer (IBM compatible, model 486). FIX DMACS was the software package for data collection and column operation. Two porous stainless steel spargers were tested (details are given in Table 1).

3.2.2 Pilot-Scale Column

The pilot-scale column (0.5 m in diameter and 4.00 m high) was also fully automated and used the same pressure transmitters, serial interface, and control software as the laboratory column (Figure 3.2). In addition, magnetic flowmeters (Fisher & Porter, model 10D1475PN11PL29) and an air flowmeter (MKS, model 1162B-400000SV) were used. Centrifugal pumps (Price, model 4MS50-SS-150 and Lobee, model 700-D-2) were used to supply wash water and pulp to the columns. The flow of feed and accepts were controlled using two control valves (DeZuric, model EP5N-DE190P-TA). Compressed air for the air flowmeter and control valves was supplied at 80 psi from the plant.

Table 3.1 Sparger characteristics.

Sparger	Length (cm)	Area (cm^2)	Nominal Pore Diameter (μm)	Permeability [33] (mDarcy)
A	10.0	78.5	0.5	0.072
B	10.0	78.5	100.0	177.05

3.3 Procedure

3.3.1 Column Operation

The level, pump speed, and gas rate were controlled using FIX DMACS with the required parameters for each test being entered into the computer. The retention time in the column was fixed by setting the accepts at a pre-determined flow. The feed flow was varied in order to maintain the froth height at a desired set point. Samples of the feed, accepts, and rejects for each test were collected for analysis. Samples were collected once steady state was achieved, and after a period of 3 times the retention time, as recommended [14].

FIX DMACS was also used for data acquisition. The following parameters were collected continuously: feed and accepts rates, gas rate, gas holdup, and level. Other parameters, such as, wash water and rejects rates were measured manually.

3.3.2 Sample Preparation

In order to measure the ERIC values for the feed and accepts streams, 4 gram pads were prepared according to the CPPA C.4U method [34]. An average of 10 ERIC values (5 per side) was obtained using a Tecnodyne ERIC 950.

Ashing was performed to determine the composition (ash and organic content) of each stream. Approximately 1 gram from each pad was placed into an oven at 575°C using ceramic crucibles. At 575°C all organic constituents (primarily fibres) are combusted, leaving inorganic material (CaO and $CaCO_3$). This ashing technique is necessary to mass balance the column.

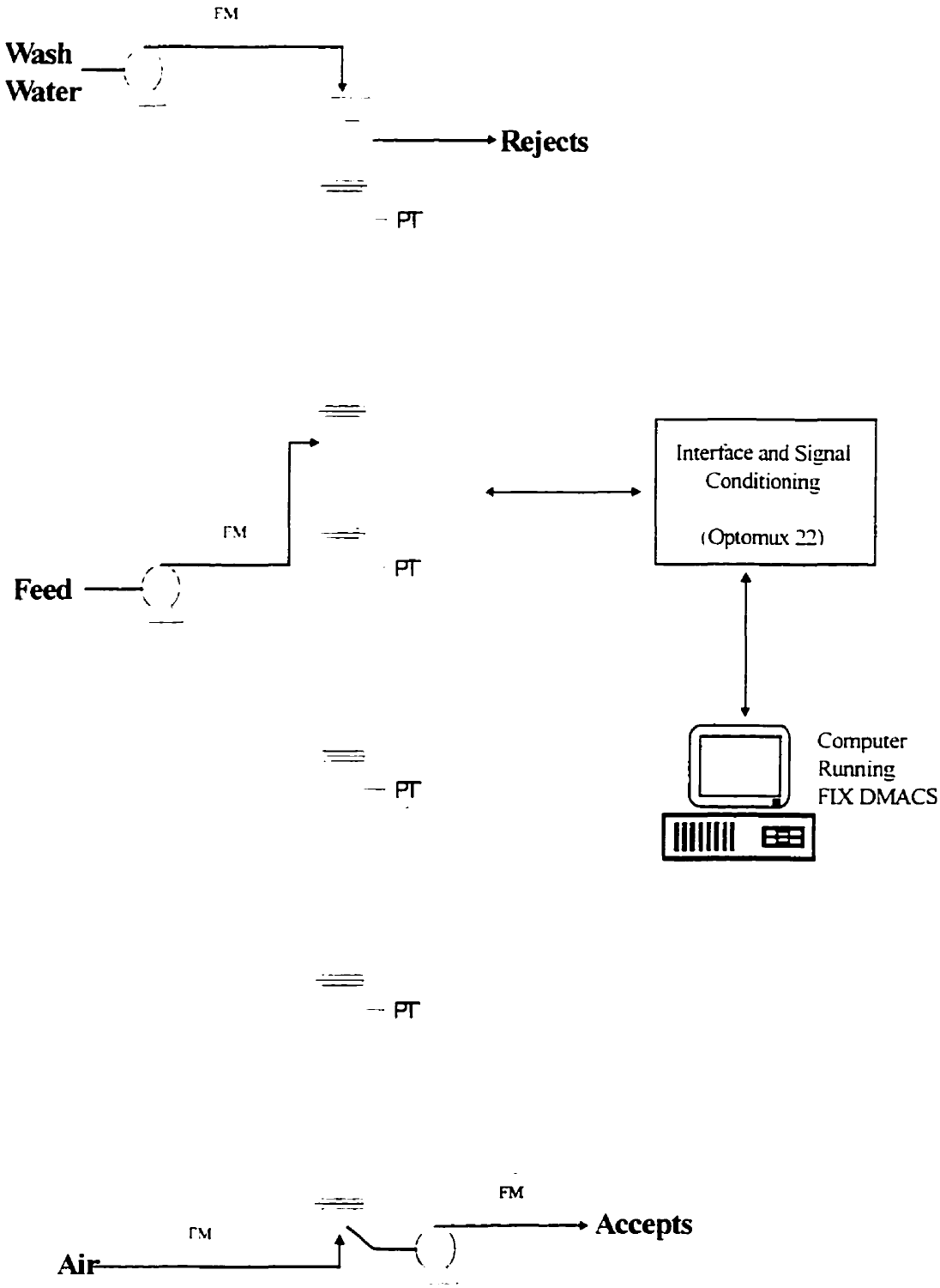

Fig. 3.1 Schematic diagram of laboratory-scale column and instrumentation: column is 10.1 cm in diameter, 4.65 m high, and divided into sections for transport.

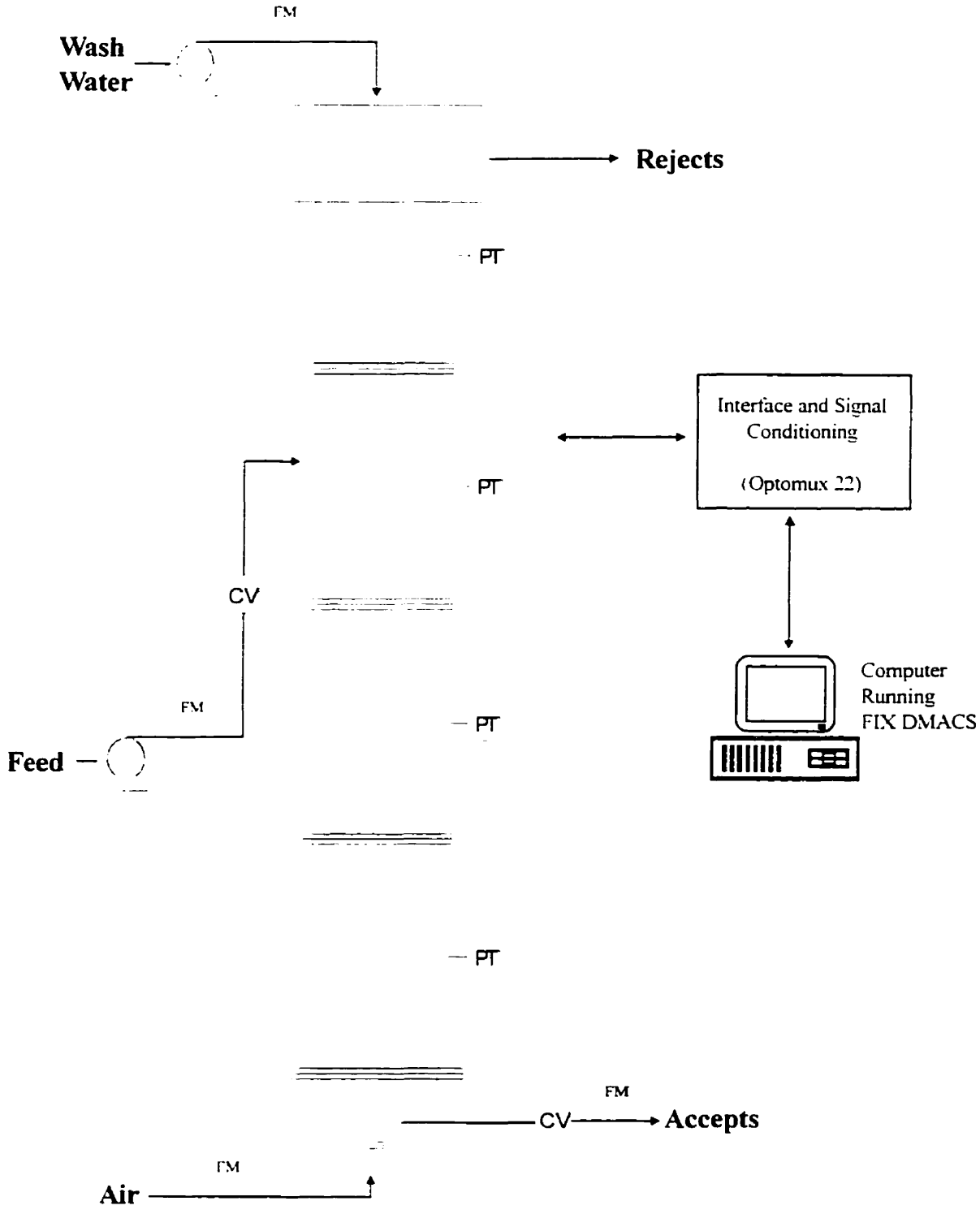

Fig. 3.2 Schematic diagram of pilot-scale column and instrumentation: column is 50 cm in diameter and 4.0 m high and divided into 1 m sections for transport.

Chapter 4: Results and Discussion

This chapter is divided in 4 parts. Part 1 is concerned with the selection of the operating conditions in the open and packed laboratory-scale columns which were subsequently used for the comparative test work reported in part 2. Part 2 is also reserved for pilot-scale comparative test work. Alternative flotation evaluation techniques, including gas surface area rate and the yield-flotation efficiency relationship, are investigated in part 3. Finally, part 4 is concerned with column scale up. All flows are expressed as superficial rates (volumetric flow per unit column cross-sectional area, Q/A_{cs}) with units of cm/s. The pulp consistency (% solids) for all experiments was maintained at approximately 1.2% by the plant. Test conditions are summarized in Appendix B. Flotation efficiency and organic loss results are presented in Appendices C and D. Results for part 3 are given in Appendix E. Appendix F is reserved for the scale up results.

4.1 Selection of Operating Conditions

4.1.1 Open Column

In order to determine the selected operating conditions in the open column the following parameters were altered in the laboratory-scale columns: gas rate, pulp retention time, froth depth, and bias rate. The effect of gas rate and retention time were

investigated using the two porous stainless steel spargers (described in Table 3.1). Column performance is usually little affected by froth height and bias rate (provided it is positive) [14], therefore only sparger A was used in testing these parameters. The selected operating conditions represent a compromise between flotation efficiency, organic loss, and operational stability.

4.1.1.1 Gas Rate

The effect of superficial gas rate (J_g) on flotation efficiency and organic loss for both spargers is shown in Figures 4.1 and 4.2 respectively. In order to isolate the effect of J_g, the retention time, froth depth, and wash water rate were maintained at constant values

For sparger A, flotation efficiency was relatively unaffected by gas rate (Fig. 4.1). At gas rates higher than 2 cm/s the flow regime of the collection zone visibly changed from bubbly to churn-turbulent. The selected superficial gas velocity for sparger A was about 1.5 cm/s. At this J_g, organic loss was approximately 4 %. It is advantageous to operate at a low value of J_g since organic loss was found to increase linearly with gas rate (Fig. 4.2).

Sparger B produced larger bubbles than sparger A and as a result lower flotation efficiencies were observed for similar values of J_g. Flotation efficiency for sparger B is more dependent on gas rate than for sparger A (Fig. 4.1). The transition to churn-turbulent flow was not observed with sparger B. This suggests that even higher gas rates could have been used to produce higher flotation efficiencies. However, at high gas rates ($J_g > 3$) it was difficult to control the froth depth, indicating that the transition to churn-turbulent does occur. Another disadvantage associated with higher gas rates is that higher organic losses occur (Fig. 4.2). Therefore, the selected J_g for sparger B was determined to be ~3 cm/s.

From Figure 4.2 it can be seen that sparger B produced lower organic losses than sparger A for all gas rates. Large bubbles (produced from sparger B) tend to carry less

water across the froth interface than small bubbles. Therefore organic loss by entrainment will be lower when larger bubbles are generated. This effect was discussed by Ajersch and Pelton [35].

4.1.1.2 Retention Time

To calculate retention time, the height of the collection zone was divided by the superficial accepts velocity, J_a. Therefore, the retention time was changed by controlling the accepts rate. The effect of retention time on flotation efficiency (Fig. 4.3) and organic loss (Fig. 4.4) was determined by setting the gas rate, froth depth, and wash water rate at pre-determined values.

Retention time had little effect on flotation efficiency when sparger A was used. Flotation efficiency was found to increase with retention time when sparger B was used. Organic loss was found to increase with retention time for both spargers. Therefore, long retention times should be avoided. The selected retention times were taken to be 6 minutes for sparger A and 8 minutes for sparger B.

4.1.1.3 Froth Depth

Flotation efficiency (Fig. 4.5) and organic loss (Fig. 4.6) were unaffected by froth depth. However, extremes in froth depth are not favorable to column operation: a shallow froth often means it is lost when surges occur; and deep froths reduce retention time. A froth depth of approximately 60 cm was determined as adequate.

4.1.1.4 Bias Rate

Bias rate was investigated using sparger A with a J_g of 1.5 cm/s. It was found that bias rate had no effect on flotation efficiency (Fig. 4.7) and organic loss (Fig. 4.8). Bias rate was found to have a slight effect on fibre loss. It was difficult to produce a froth with no wash water (negative bias). Therefore, a bias rate of about 0.16 cm/s was selected. High bias rates are to be avoided since they reduce retention time and dilute the accepts.

Figure 4.8 indicates that bias rate has no effect on organic loss. However, visual inspection of the reject pads indicate that the pads become more fibrous as the wash water is reduced. Fibrous pads contain large amounts of long fibres [36]. Long fibres report to the rejects primarily due to entrainment. Wash water is effective in removing the long fibres (reject pads at high J_b are not 'hairy'). At high bias rates other organic material is entering the froth and maintaining the organic loss value constant.

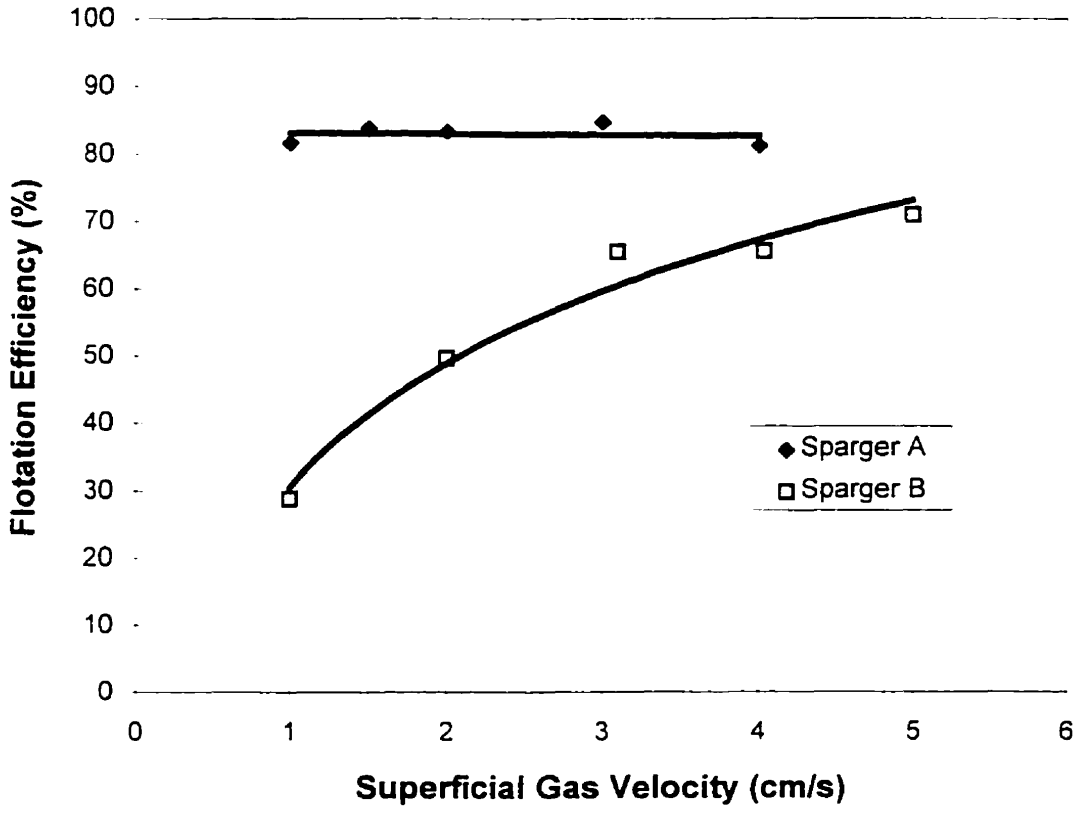

Fig. 4.1 Flotation efficiency versus superficial gas velocity (open column). Conditions: retention time = 8 minutes; froth depth = 50 cm; bias rate = 0.16 cm/s.

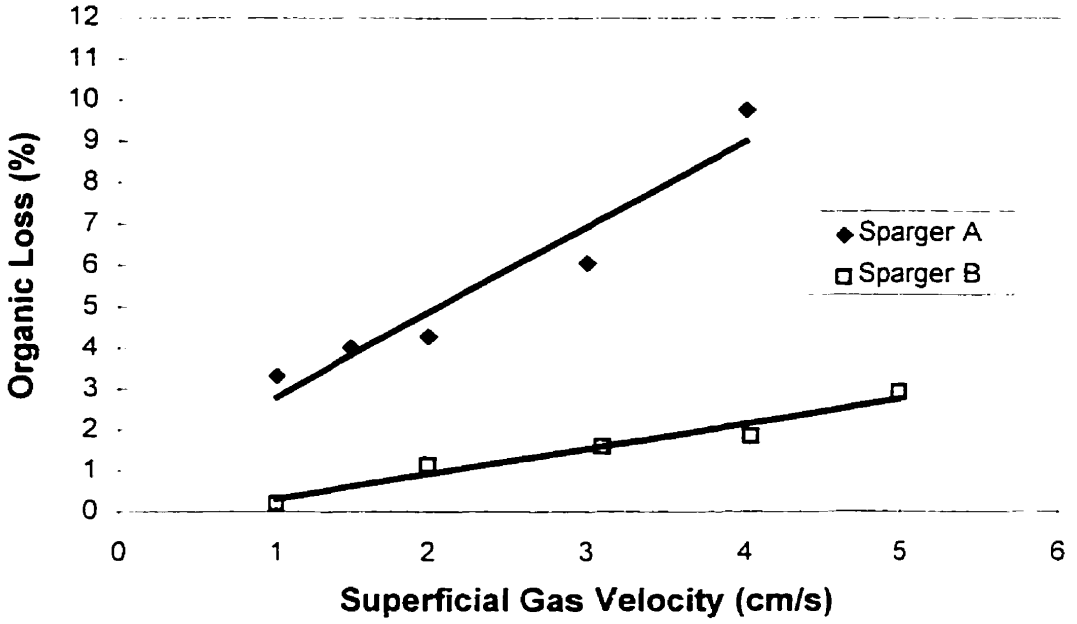

Fig. 4.2 Organic loss versus superficial gas velocity (open column). Conditions: see Fig. 4.1.

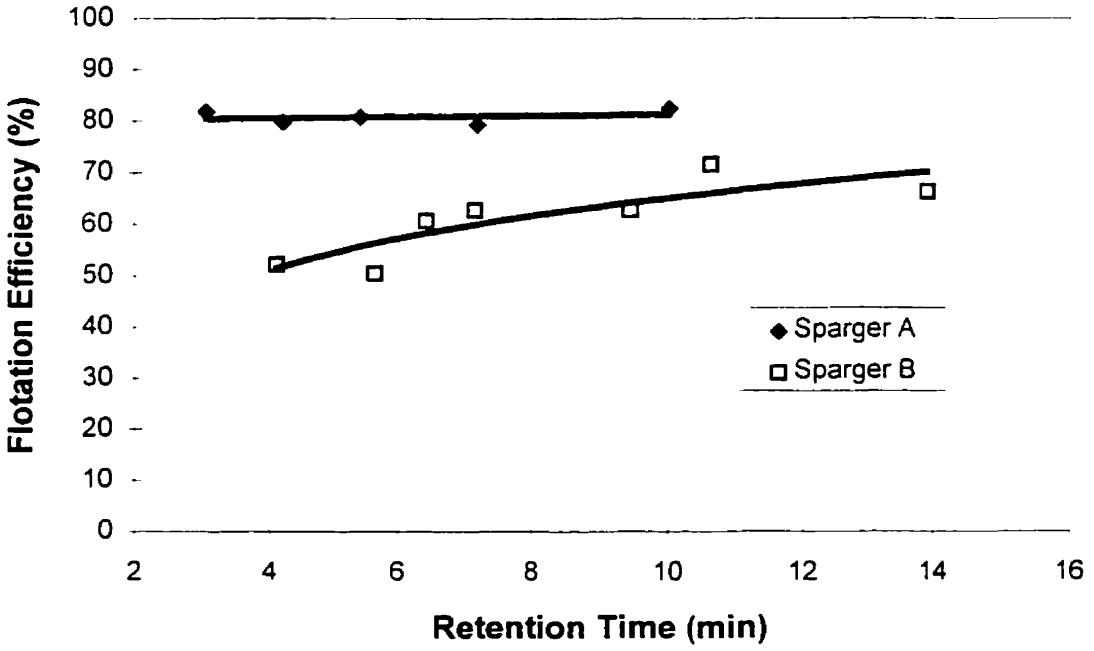

Fig. 4.3 Flotation efficiency versus retention time (open column). Conditions: gas rate = 1.5 cm/s (sparger A) and 2.0 cm/s (sparger B); froth height = 50 cm; bias rate = 0.16 cm/s.

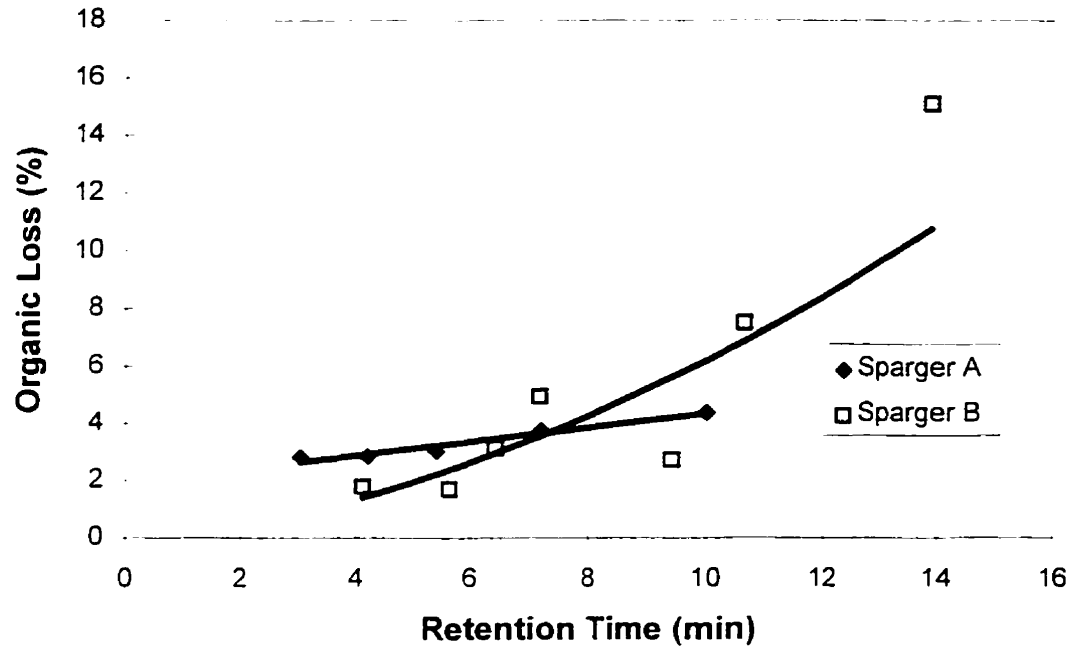

Fig. 4.4 Organic loss versus retention time (open column). Conditions: see Fig. 4.3.

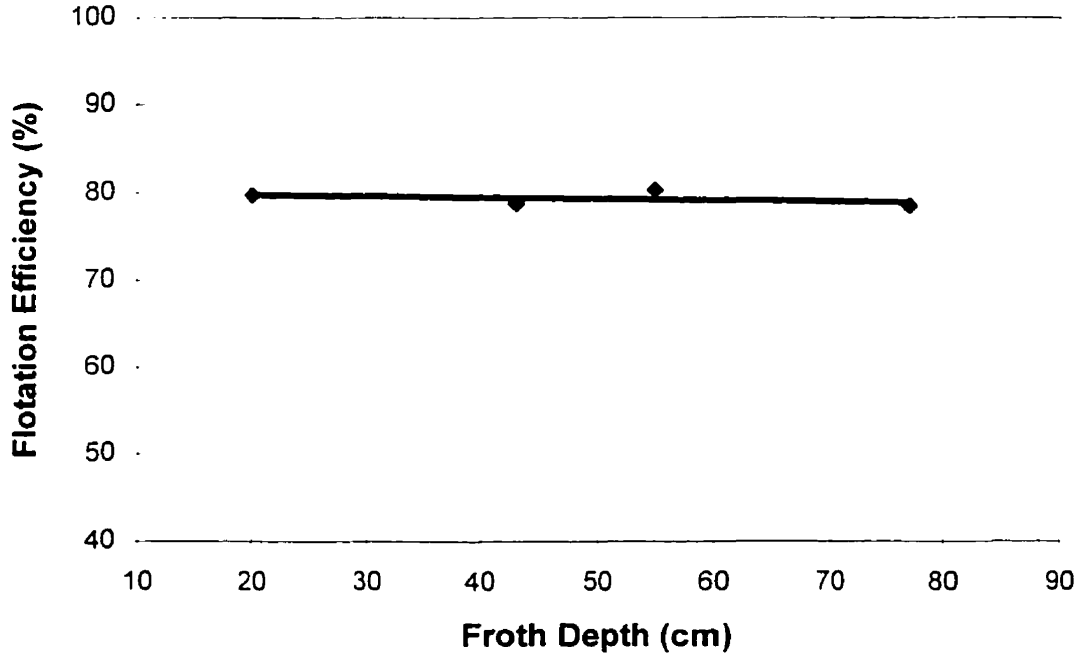

Fig. 4.5 Flotation efficiency versus froth depth (open column). Conditions: sparger A; gas rate = 1.5 cm/s; retention time = 6 minutes; bias rate = 0.16 cm/s.

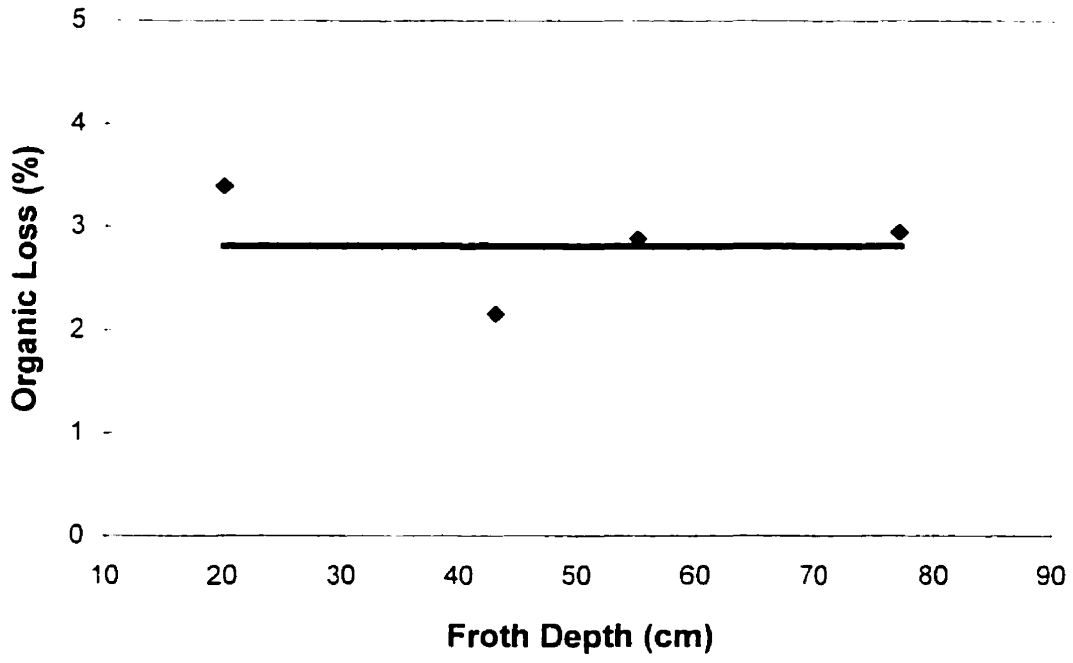

Fig. 4.6 Organic loss versus froth depth (open column). Conditions: see Fig. 4.5.

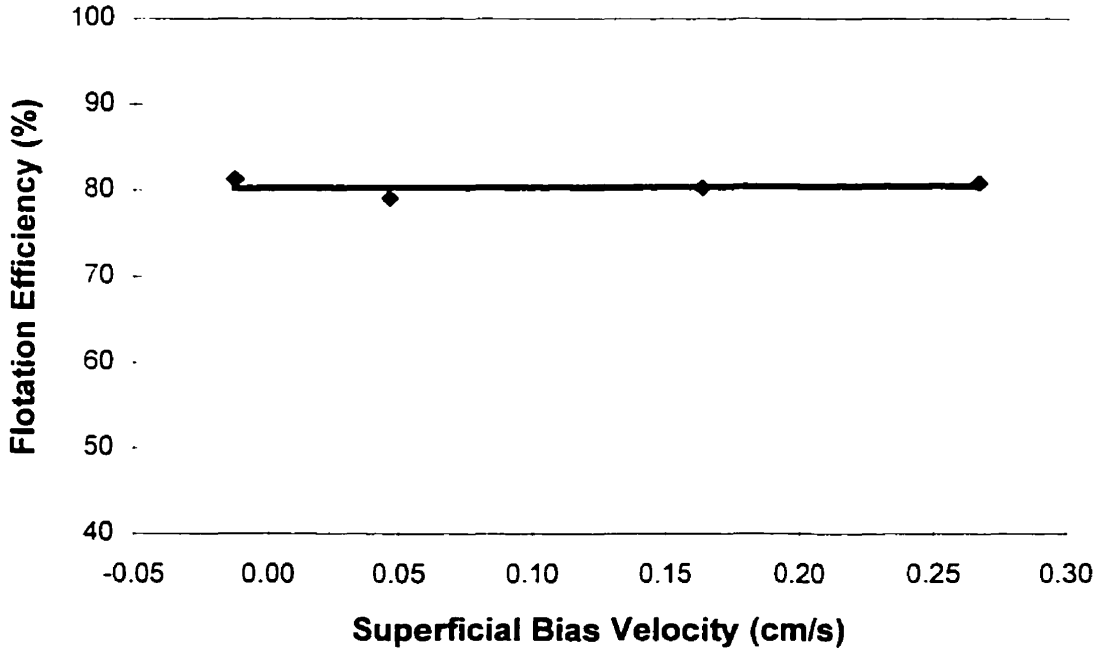

Fig. 4.7 Flotation efficiency versus bias rate (open column). Conditions: sparger A; gas rate = 1.5 cm/s; retention time = 6 minutes; froth depth = 50 cm.

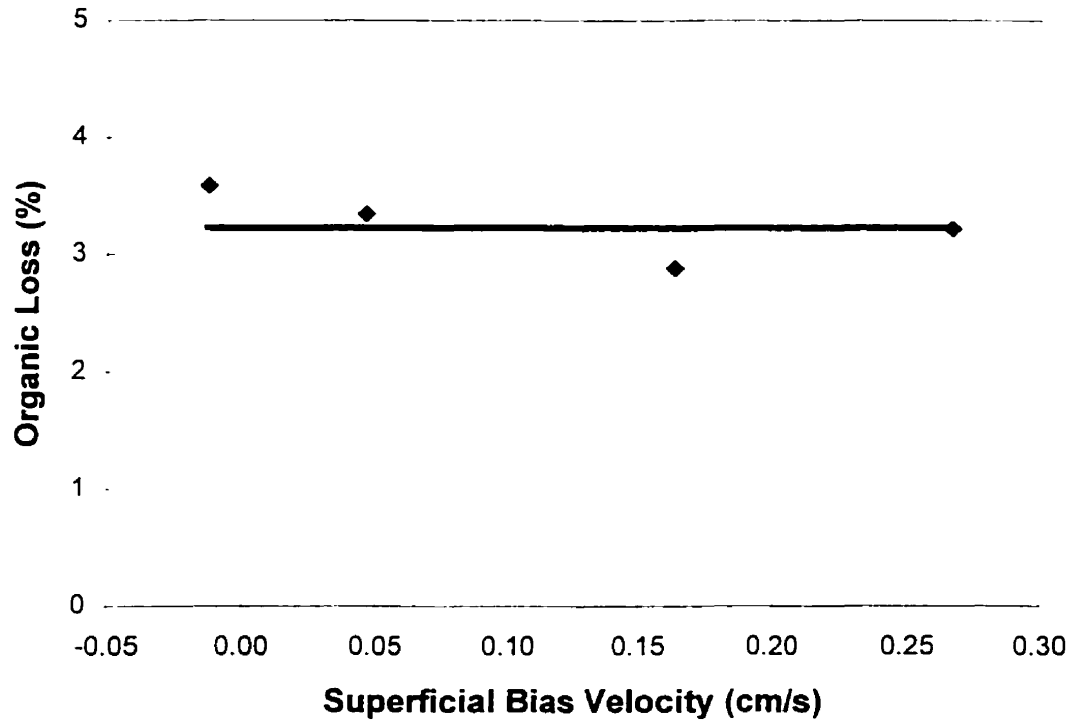

Fig. 4.8 Organic loss versus bias rate (open column). Conditions: see Fig. 4.7.

4.1.2 Packed Column

The operating variables tested in the packed laboratory-scale column were the gas rate and retention time. Froth depth and bias rate had little effect on flotation efficiency and organic loss from the open column tests, therefore the same values were chosen for the packed column.

4.1.2.1 Gas Rate

The effect of J_g on performance for the different spargers is shown in Fig. 4.9 (flotation efficiency) and 4.10 (organic loss). To determine the effect of J_g, the retention time, froth depth, and bias rate were maintained constant.

For sparger A, the selected J_g was determined to be about 2 cm/s (Fig. 4.9). At J_g less than 2 cm/s pulp accumulated in the packing. At J_g greater than 2 cm/s it became

difficult to control the froth depth due to a change in flow regime from bubbly to churn-turbulent. At this J_g, the organic loss was approximately 4.5% (Fig. 4.10).

Superficial gas velocity had a similar effect on flotation efficiency when sparger B and no sparger were used (Fig. 4.9). (The performance of sparger B and no sparger cannot be compared at this point since the experiments were performed with different feed consistencies due to plant variations.) The selected J_g for sparger B was determined to be 3 cm/s since above this the froth depth could no longer be controlled easily. When no sparger was used the transition in the collection zone to churn-turbulent was not observed until higher values of J_g. Therefore, a J_g of about 4 cm/s was selected when no sparger was used. At their selected values of J_g, sparger B and no sparger produced organic losses less than 2% (Fig. 4.10).

4.1.2.2 Retention Time

The effect of retention time was only investigated using sparger B and no sparger. The effect on flotation efficiency (Fig. 4.11) and organic loss (Fig. 4.12) was determined by setting the gas rate, froth depth, and bias rate at the selected values. Retention time had no effect on flotation efficiency when sparger A was used in the open column, and thus was assumed to be the case in the packed column. As a result, the selected retention time for sparger A was taken to be about 6 minutes. Retention time had a similar effect on flotation efficiency and organic loss when sparger B and no sparger were used. The selected retention time for sparger B and no sparger was determined to be approximately 8 minutes.

A summary of the selected operating conditions for the packed column is given in Table 4.1 along with those previously selected for the open column.

Table 4.1 Summary of selected operating conditions laboratory columns.

Column	Sparger	J_g (cm/s)	Retention Time (min.)	Froth Depth (cm)	Bias Rate (cm/s)
open	A	1.5	6	60	0.16
open	B	3.0	8	60	0.16
packed	A	2.0	6	60	0.16
packed	B	3.0	8	60	0.16
packed	none	4.0	8	60	0.16

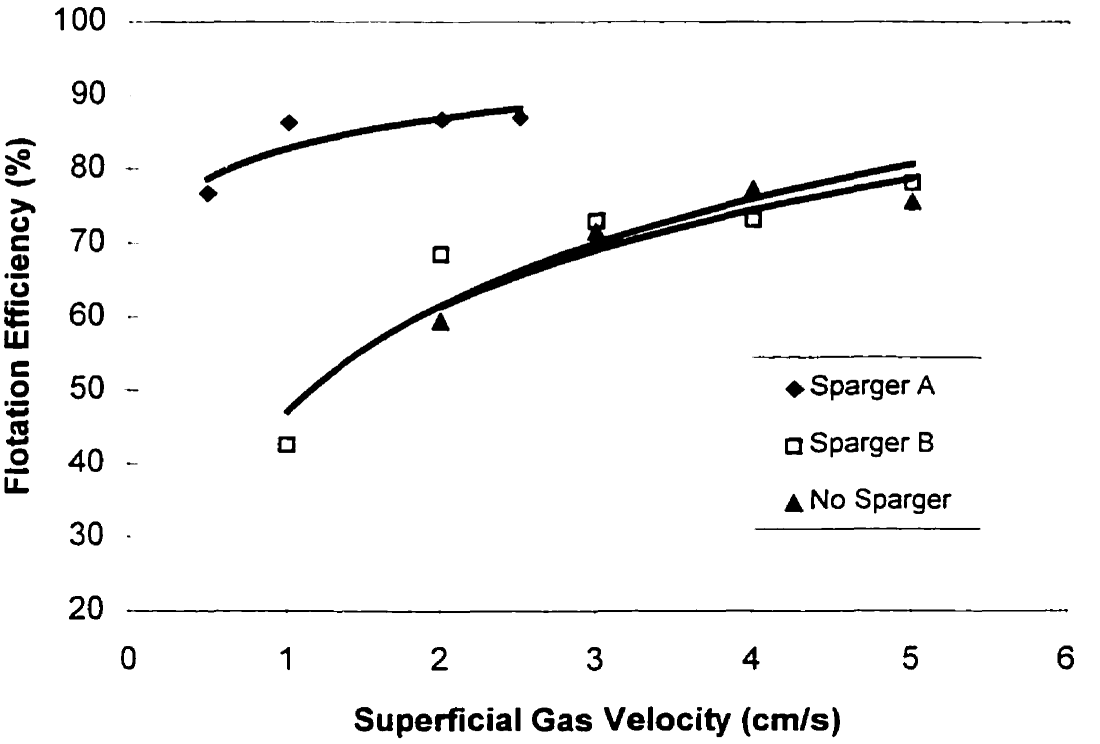

Fig. 4.9 Flotation efficiency versus superficial gas velocity (packed column). Conditions: retention time = 8 minutes; froth depth = 60 cm; bias rate = 0.16 cm/s.

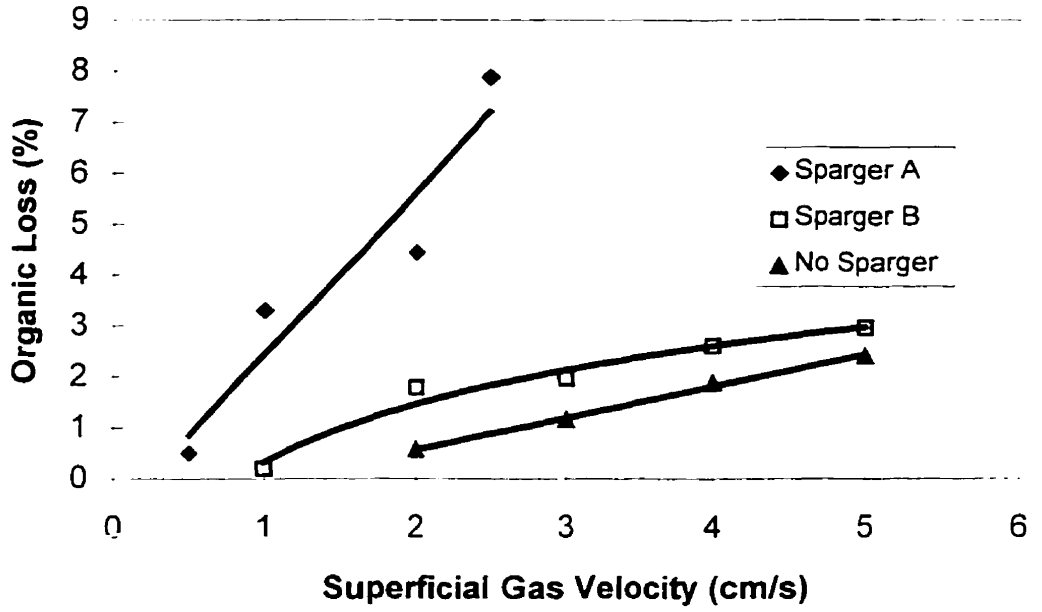

Fig. 4.10 Organic loss versus superficial gas velocity (packed column). Conditions: see Fig. 4.9.

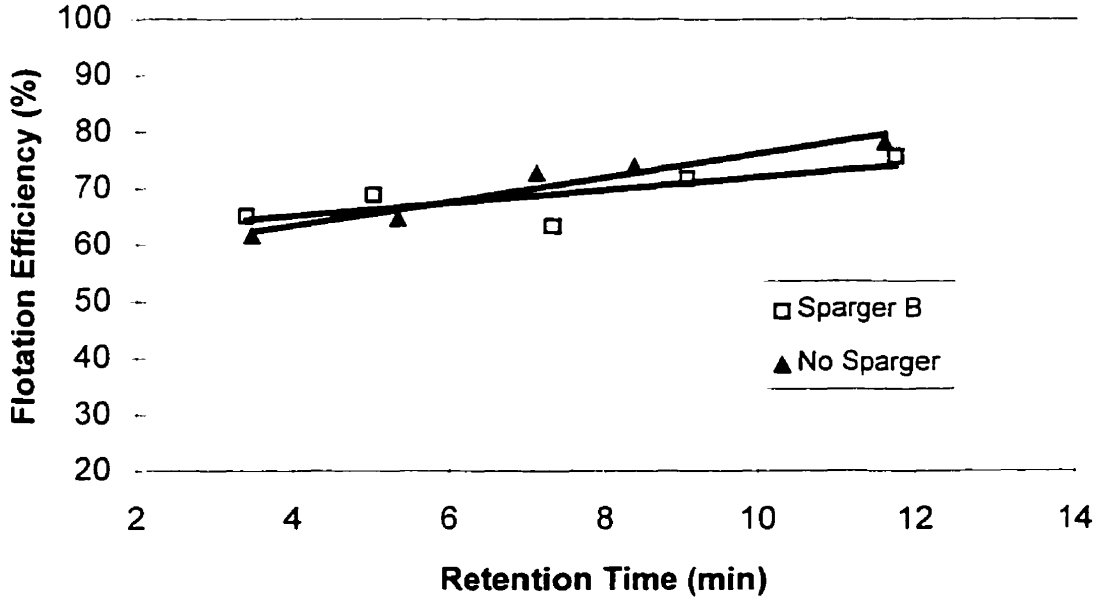

Fig. 4.11 Flotation efficiency versus retention time (packed column). Conditions: gas rate = 3.0 cm/s (sparger B) and 4.0 cm/s (no sparger); froth depth = 60 cm; bias rate = 0.16 cm/s.

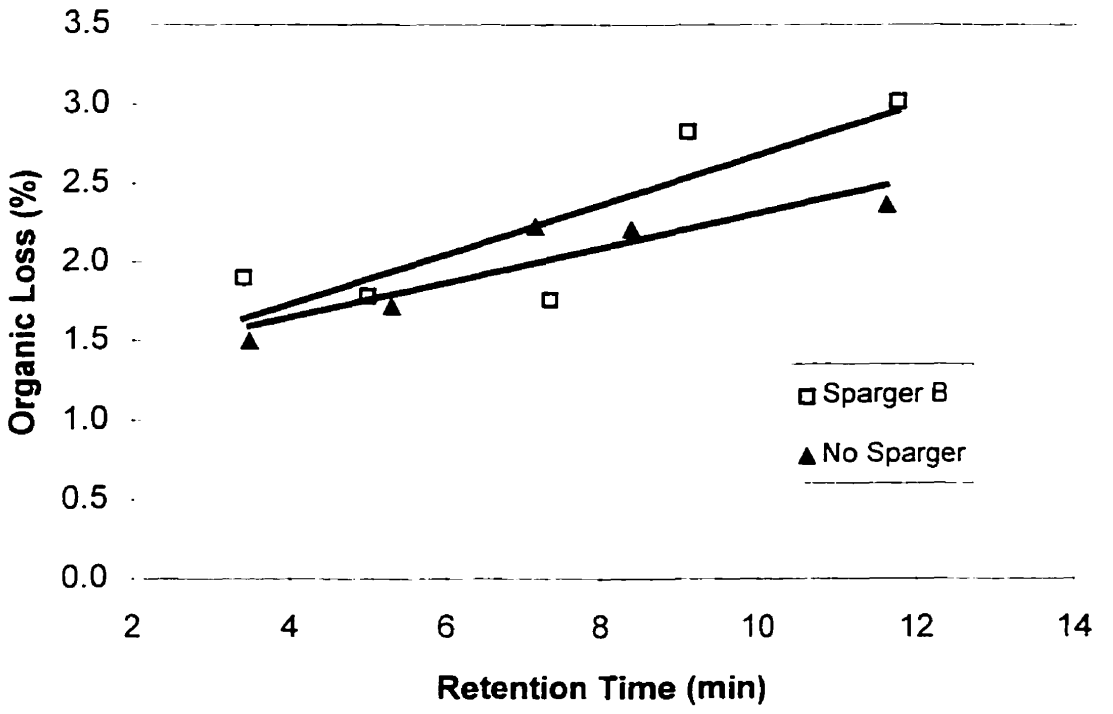

Fig. 4.12 Organic loss versus retention time (packed column). Conditions: see Fig. 4.11.

4.2 Comparison of Columns and Mechanical Cells

4.2.1 Laboratory-Scale Comparison

The laboratory-scale columns were compared at their selected operating conditions (Table 4.1) and compared to the mechanical cells. The columns were run for 3 hours with 4 samples from each column being collected and analyzed. All the experiments were completed during a 30 hour period so that the feed from the plant would remain relatively constant to permit the comparison. Samples from the mechanical cell circuit were also taken during this time period. Certain experiments were repeated two weeks later to test reproducibility.

The open and packed columns using sparger A equaled the performance of the mechanical cells in terms of flotation efficiency (Fig. 4.13 and Table 4.2). The packed

column using sparger B also produced a similar flotation efficiency to the mechanical cells. The open column using sparger B and the packed column using no sparger had similar flotation efficiencies and were both inferior to the mechanical cells. The experiments with sparger B were repeated and compared to the mechanical cells. In this case, all three were statistically indistinguishable in terms of flotation efficiency (Table 4.3). When sparger A was used a drop in gas holdup with time was observed, indicating that the sparger was becoming blocked. This phenomenon did not occur with sparger B.

Sparger A in the open and packed columns produced the highest organic loss (Fig. 4.14 and Table 4.2). The packed column using no sparger yielded the lowest organic loss. The organic loss for the mechanical cell circuit at this stage could not be determined since an accurate flow rate of the rejects could not be obtained. All of the organic losses from the columns were less than 2%.

Experiments were also performed in both columns using sparger B and in the packed column with no sparger without wash water. Without wash water, a froth could not be produced. The bias water replaces the water naturally drained from the froth [14]. Therefore wash water is essential when sparger B and no sparger are to be used.

Flotation efficiency and organic loss results were also plotted versus time (Fig. 4.15 and 4.16) to show the effect of the standard deviation.

Table 4.2 Average flotation efficiency and organic loss for columns and mechanical cells. Variation is given as a 95% confidence interval.

Flotation Cell	Sparger	Flotation Efficiency (%)	Organic Loss (%)
open column	A	81.7 ± 0.6	1.6 ± 1.0
open column	B	72.3 ± 1.6	1.3 ± 0.2
packed column	A	79.9 ± 0.7	1.7 ± 0.1
packed column	B	79.6 ± 1.6	0.9 ± 0.2
packed column	none	73.3 ± 1.4	0.6 ± 0.1
mechanical	-	79.2 ± 1.0	N/A

Table 4.3 Average flotation efficiency and organic loss for columns using sparger B and mechanical cells (repeat). Variation is given as a 95% confidence interval.

Flotation Cell	Sparger	Flotation Efficiency (%)	Organic Loss (%)
open column	B	76.0 ± 1.4	1.9 ± 0.6
packed column	B	76.0 ± 0.9	1.7 ± 0.2
mechanical	-	77.3 ± 0.4	N/A

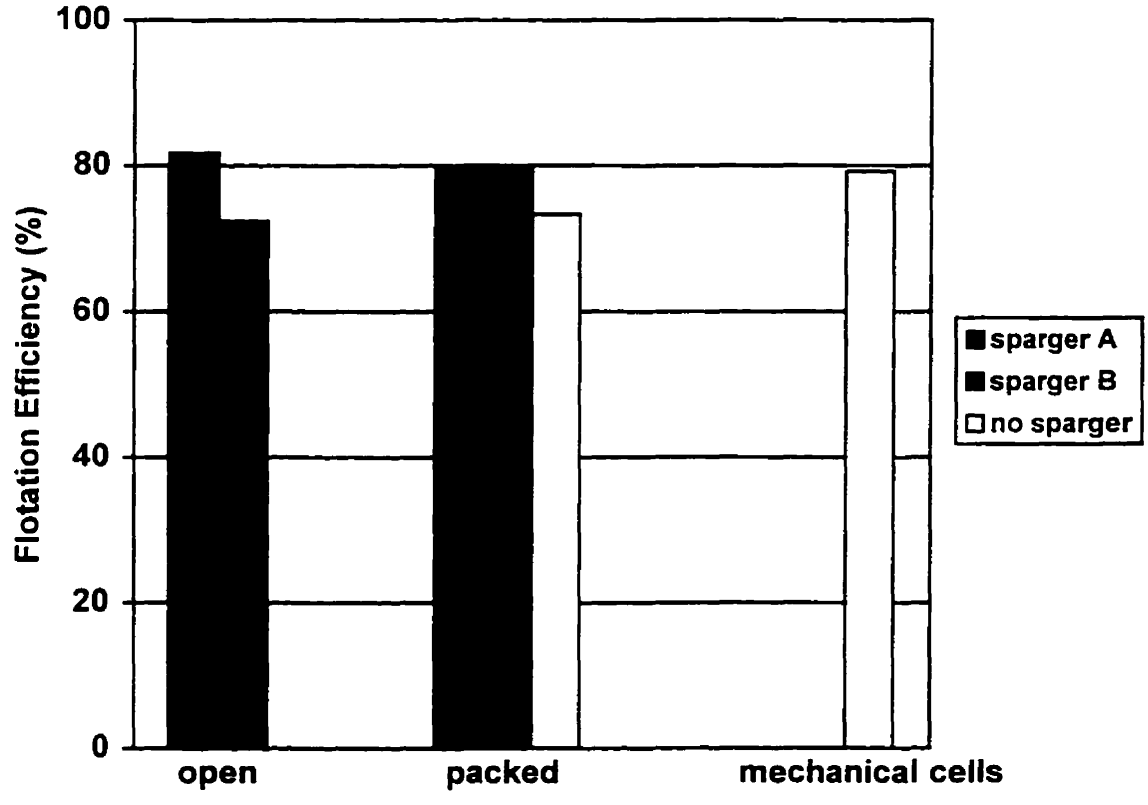

Fig 4.13 Flotation efficiency results (laboratory column). Conditions: see table 4.1.

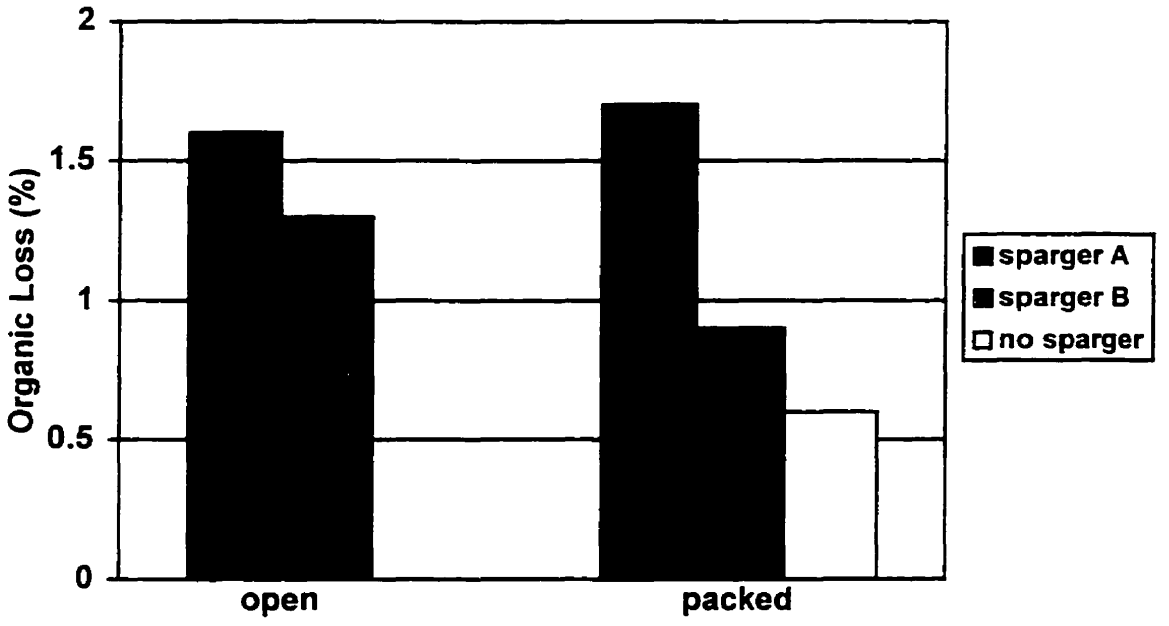

Fig. 4.14 Organic loss results (laboratory column). Conditions: see table 4.1.

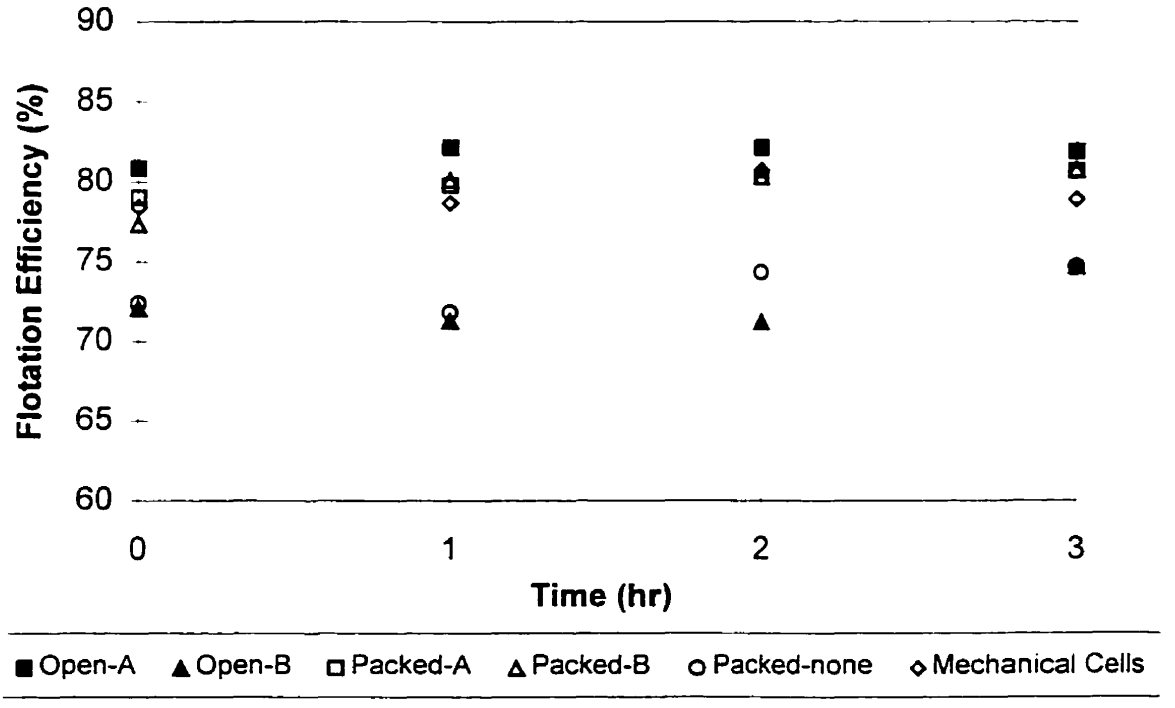

Fig. 4.15 Flotation efficiency versus time (laboratory column). Conditions: see Table 4.1.

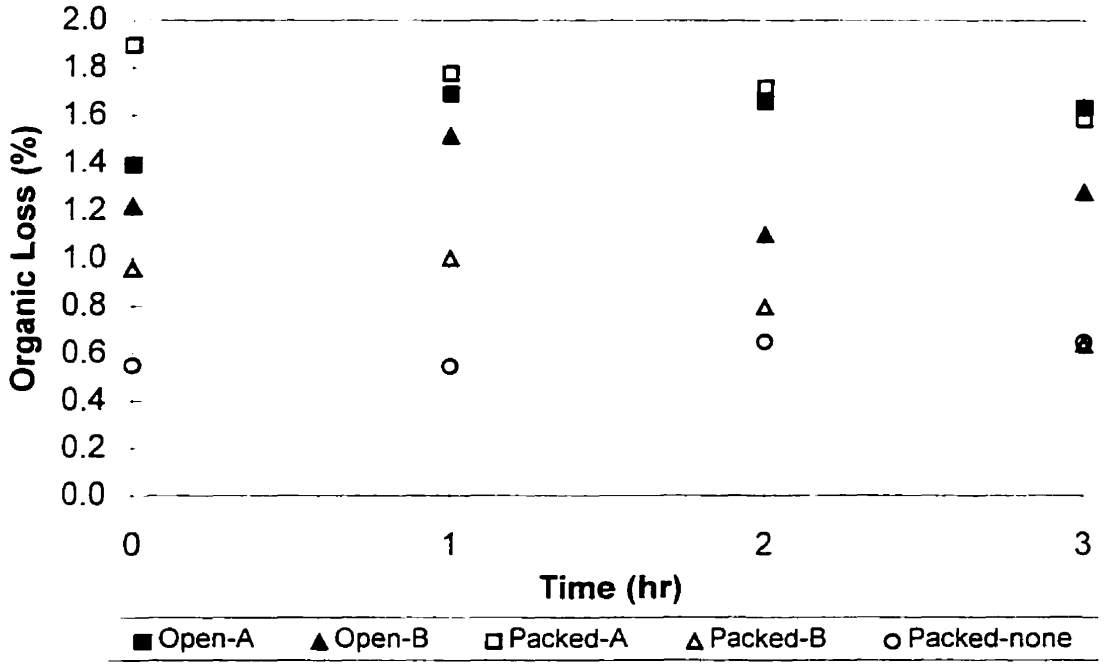

Fig. 4.16 Organic loss versus time (laboratory column). Conditions: see Table 4.1.

4.2.2 Pilot-Scale Comparison

The open and packed pilot columns were operated with a variable gap sparger and with no sparger (in the case of packing) for extended periods of time. The operating conditions for the columns and the length of test are presented in Table 4.4. Higher residence times could not be obtained due to the absence of an accepts pump. Samples from the columns and mechanical cells were collected every two hours.

Table 4.4 Summary of operating conditions in pilot columns.

Column	Sparger	Test Duration (hr)	J_g (cm/s)	Residence Time (min)	Froth Depth (cm)	Bias Rate (cm/s)
open	variable gap	12	2.9	12.3	65	0.15
packed	variable gap	22	2.8	13.4	59	0.17
packed	none	6	3.4	11.8	61	0.16

The open and packed columns had average flotation efficiencies which were inferior to that of the mechanical cells (Fig. 4.17 and Table 4.5). The packed column using the variable gap sparger had higher flotation efficiencies than the open column. The open column and the packed column with no sparger had similar flotation efficiencies.

The average organic loss from all of the columns was less than 3% (Fig. 4.18 and Table 4.5). In all cases the columns had lower organic losses than the mechanical cells. The average organic loss from the mechanical cells was 8.5% (Fig. 4.18 and Table 4.5). Organic loss data for the packed column with the sparger are not available at 8 and 10 hours due to operational difficulties.

The flotation efficiency results for the packed column with a sparger (Fig. 4.17) remained relatively constant (standard deviation of 2.5%) during the 22 hour test period. As a result, pulp accumulation in the packing and in the sparger did not occur or did not affect the performance of the packed column with time.

Table 4.5 Average flotation efficiency and organic loss for columns and mechanical cells. Variation is given as a 95% confidence interval.

Flotation Cell	Sparger	Flotation Efficiency (%)	Organic Loss (%)
open column	variable gap	65.3 ± 2.9	2.2 ± 0.3
packed column	variable gap	72.9 ± 1.4	1.8 ± 0.3
packed column	none	67.0 ± 3.1	1.8 ± 2.3
mechanical	-	80.5 ± 1.2	8.5 ± 0.6

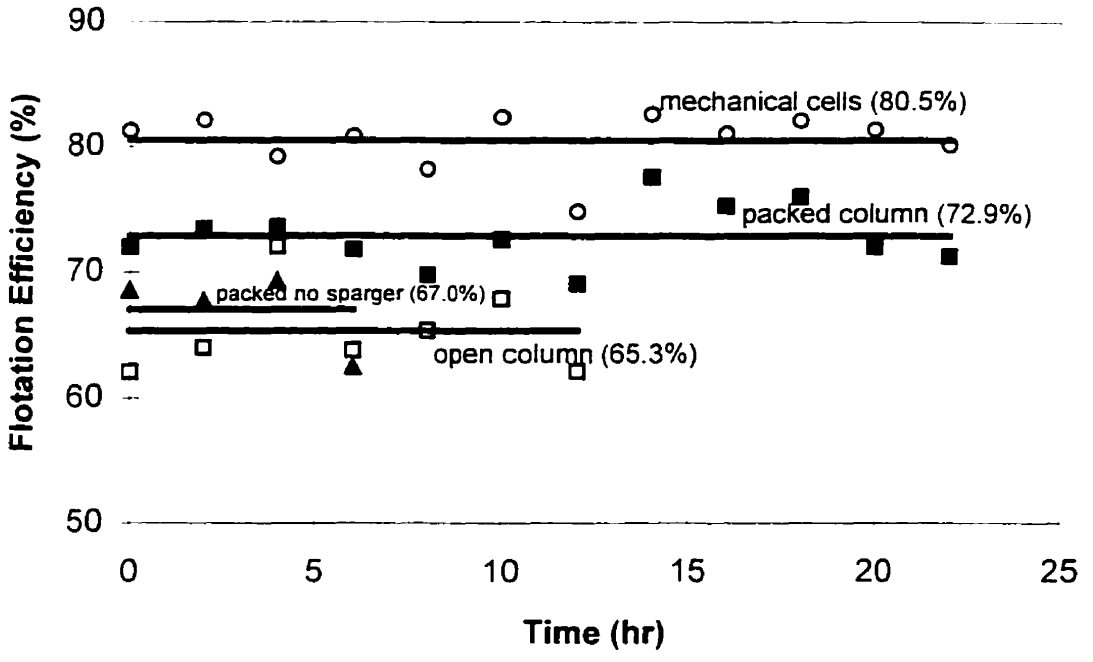

Fig. 4.17 Flotation efficiency versus time (pilot column). Conditions: see Table 4.5.

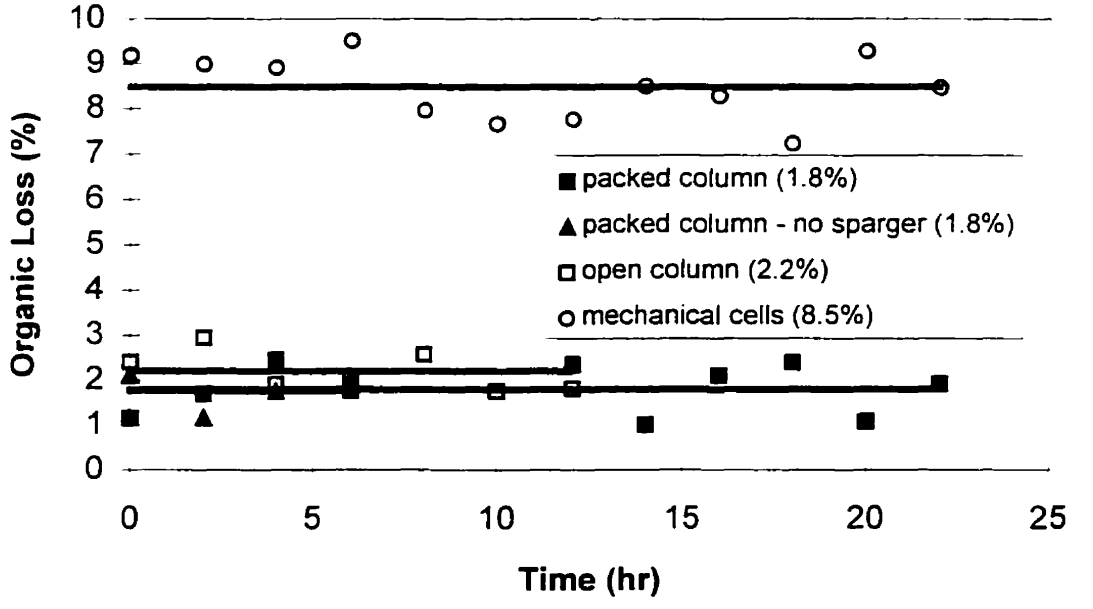

Fig. 4.18 Organic loss versus time (pilot column). Conditions: see Table 4.5.

4.3 Alternative Flotation Evaluation Techniques

4.3.1 Bubble Surface Area Generation Rate

The surface area generation rate of bubbles is the parameter which governs the solids removal rate. By increasing the bubble surface area available for particle attachment more solids will be removed. Bubble surface area generation rate is useful for relating flotation efficiency since surface area rates incorporate bubble size and gas velocity (eq. 2.11).

Figure 4.19 shows the effect of surface area generation rate on flotation efficiency in the open laboratory-scale column. The curve in Fig. 4.19 was constructed using data from sparger B (coarse sparger, producing large bubbles) and from sparger A (fine sparger, producing small bubbles). The right side of the curve (produced by sparger A) forms a plateau since the maximum flotation efficiency was reached when sparger A was used. The left side of the curve (produced by sparger B) increases linearly until the maximum flotation efficiency for sparger B is reached. It can be seen that a relationship exists between flotation efficiency and bubble surface area generation rate. If the gas rate were increased with sparger B, the left portion of Fig. 4.19 would approach the plateau obtained with sparger A. Similarly, the right portion of Fig. 4.19 should decrease linearly as the gas rate is decreased. The same relationship between flotation efficiency and bubble surface area generation rate is observed in the packed laboratory-scale column (Fig. 4.20).

From the extrapolated portions of Figures 4.19 and 4.20 the transition to maximum flotation efficiency occurs at a bubble surface area generation rate of approximately 35 s^{-1}. Therefore, the combination of bubble size (governed by sparger type and surfactant dosage) and gas rate which yields a bubble surface area generation rate of 35 s^{-1} will produce the maximum flotation efficiency. Additional work is required to completed the interpolated portions of Figures 4.19 and 4.20. This can be accomplished by testing spargers with intermediate porosities at different gas velocities.

The dashed interpolations of Figures 4.19 and 4.20 will only be obtained if there is no regime change, i.e. if the flow remains bubbly over the entire range of generation rates.

The average surface area generation rates for the open and packed pilot columns were 22.6 and 23.4 s^{-1} (Appendix E). Both of these values are below the theoretical maximum of 35 s^{-1} obtained from the laboratory-scale columns. Therefore, the low flotation efficiencies obtained in the pilot column are reflected in the low surface area generation rates.

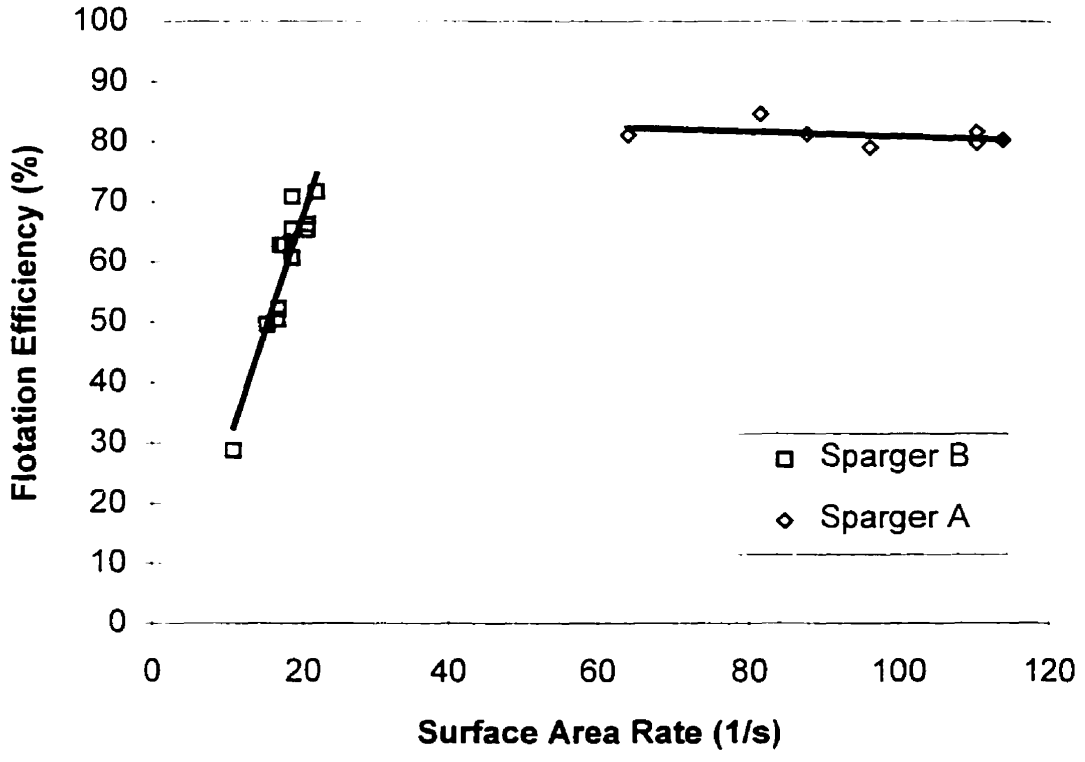

Fig. 4.19 Flotation efficiency versus bubble surface area rate in the open laboratory column.

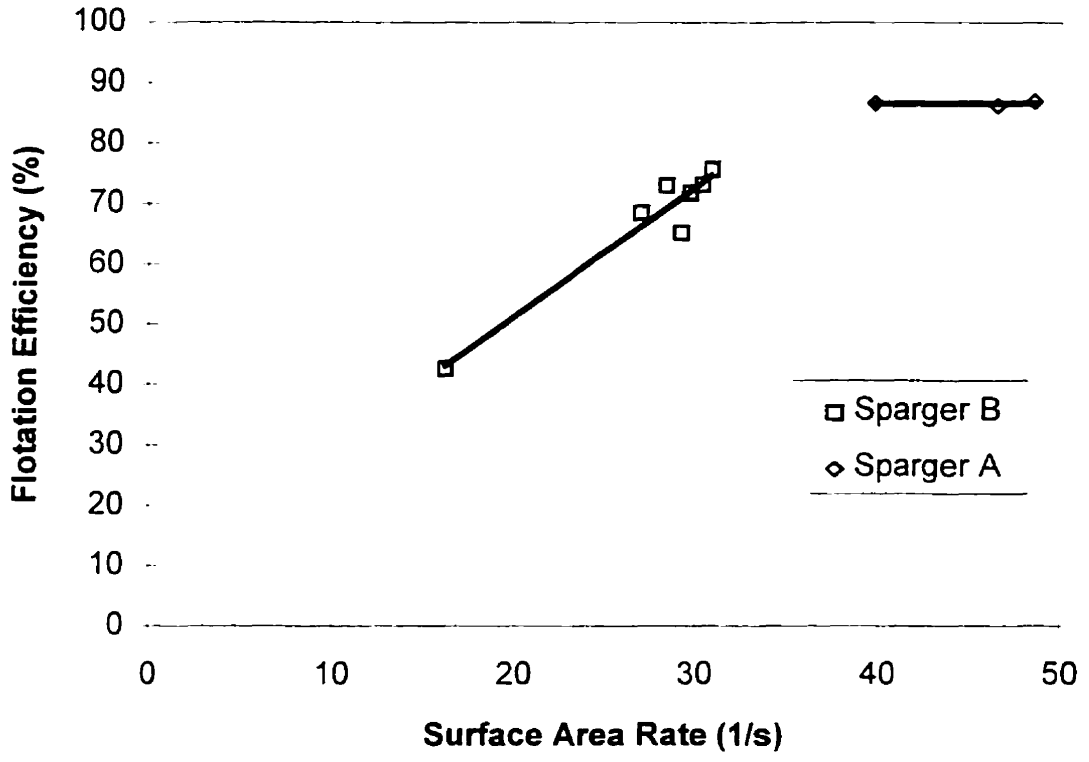

Fig. 4.20 Flotation efficiency versus bubble surface area rate in the packed laboratory column.

4.3.2 Yield - Flotation Efficiency Relationship

Recovery-grade relationships are used to assess mineral flotation. In flotation deinking, recovery translates to organic yield and grade refers to the accepts pulp quality (flotation efficiency). Figure 4.21 is a yield-flotation efficiency curve for the open and packed laboratory columns. It can be seen that as flotation efficiency increases yield decreases and vice versa. To a first approximation all forms of column operation follow the same relationship. Feed variations make an absolute relationship impossible. It may be necessary to construct several yield-efficiency curves to take all plant variations into account.

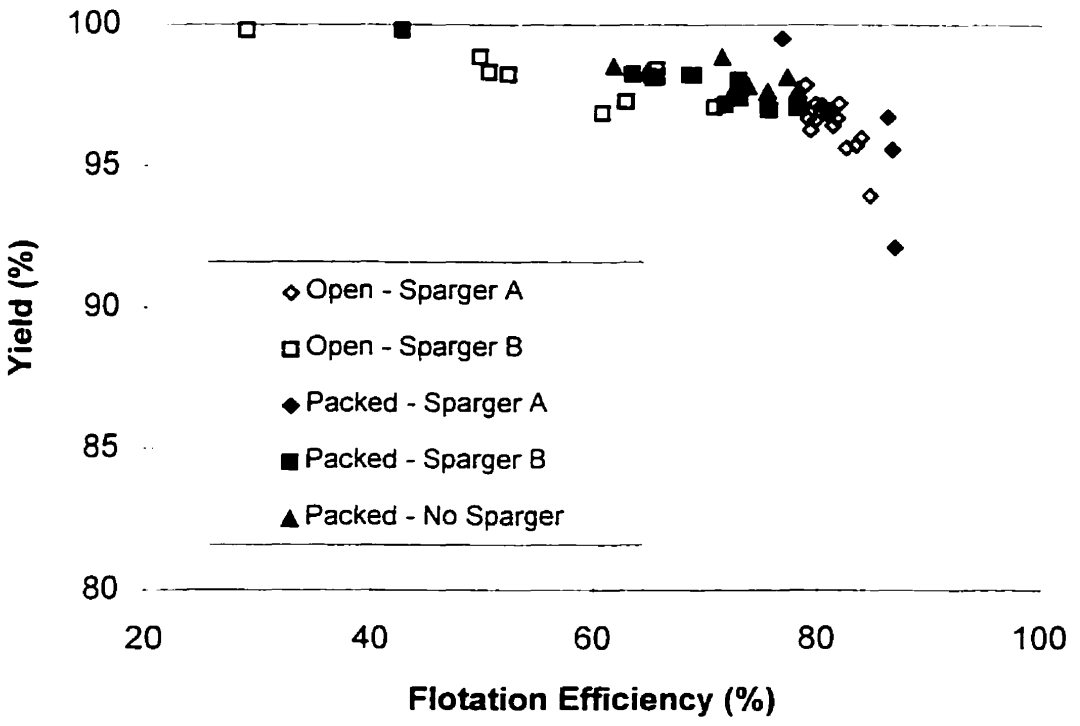

Fig. 4.21 Yield-flotation efficiency relationship for open and packed laboratory-scale columns.

4.4 Evaluation of Column Scale Up Procedure

In addition to the comparative test work described in section 4.2.2, the pilot scale column was used as an intermediate step to evaluate the scale up procedure. The open and packed pilot columns were operated at selected operating conditions (Table 4.4) using a variable gap sparger. In order to scale up, ink recovery was used as a means to assess column performance. Ink recovery is described in section 2.5.1.2 (equation 2.31). Using data from the laboratory column coupled with pilot column dimensions, predicted pilot column recoveries were calculated. Laboratory column data was collected using a porous stainless steel sparger (sparger B). Sparger B was chosen for the laboratory column since it gave a similar gas holdup versus gas rate relationship as the variable gap

sparger in the pilot column (Fig. 4.22). All data for the pilot column scale up is presented in Table 4.6 and Appendix F.

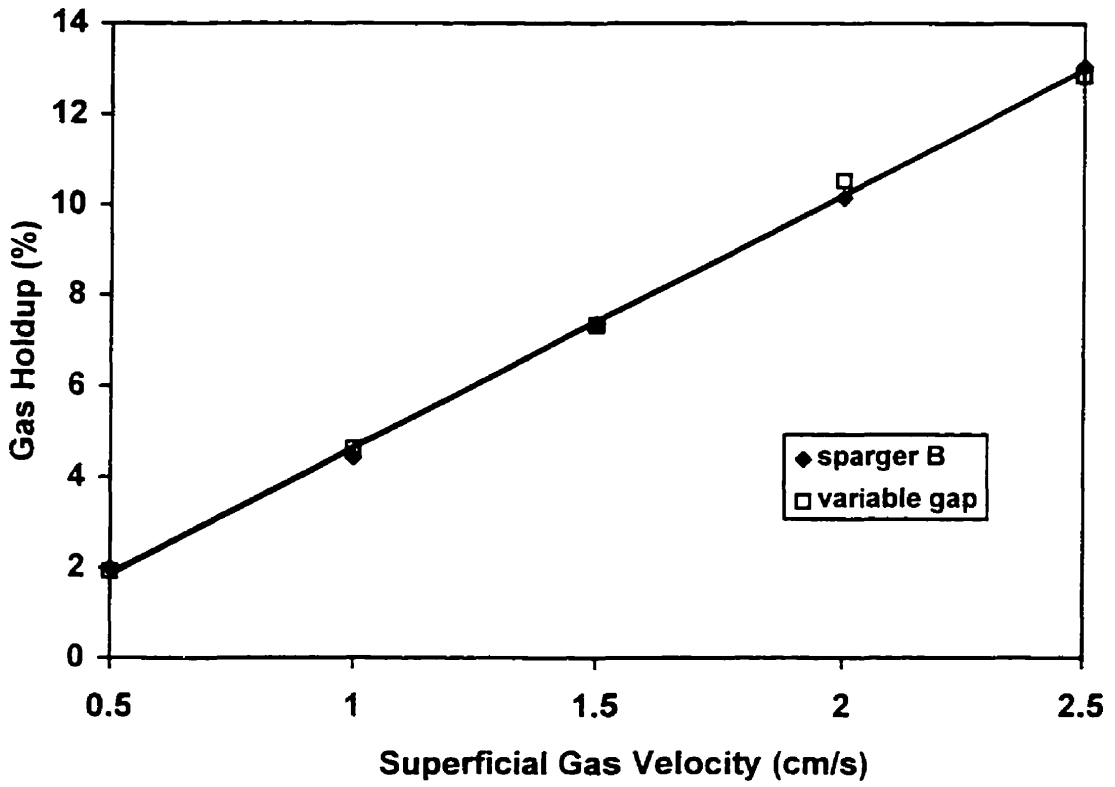

Fig. 4.22 Gas holdup versus gas velocity relationship for the variable gap sparger (operated at 50 psi) in the pilot column and the porous sparger (sparger B) in the laboratory column.

In order to calculate ink recoveries, an equilibrium ink recovery was estimated. The highest recovery obtained with sparger A was 87%. Therefore R_{eq} was estimated at 87%.

The predicted ink recovery in the open pilot column was calculated using the plug flow dispersion (P.F.D.) model [14]. The P.F.D. model predicts the degree of mixing in the pilot column. The predicted and experimental ink recoveries in the open pilot column were 58.1% and 63.5%, respectively.

One of the reported technical advantages of packed column flotation is that packing reduces mixing [19]. If mixing were completely eliminated then the plug flow (P.F.) model could be used for calculating the predicted ink recoveries in the packed pilot column. With the variable gap sparger the predicted P.F. and P.F.D. recoveries were calculated to be 80.7 and 65.1%. The experimental recovery in both cases was 70.9%. The percent difference between the predicted and experimental recoveries for the P.F. model was 12.1%. The percent difference in the case of the P.F.D. model was 8.9%. When no sparger was used in the packed column the percent difference between the predicted and experimental recoveries for the P.F. and P.F.D. models were 22.1 and 2.4%. Therefore the P.F.D. model, in the present case, appears to be more accurate than the P.F. model for scaling up packed columns. When scaling up columns it is appropriate to underestimate the recovery (lower predicted than experimental recovery). If recovery is over predicted then smaller columns will be designed which may prove incapable of reaching the target recovery.

Table 4.6 Summary of pilot column scale up.

Column	Sparger	Model	$Recovery_{pred.}$ (%)	$Recovery_{exp.}$ (%)	$(R_t - R_e)/R_t$ (%)
open	variable gap	P.F.D.	58.1	63.5	-9.3
packed	variable gap	P.F.	80.7	70.9	+12.1
	variable gap	P.F.D.	65.1	70.9	-8.9
	none	P.F.	79.5	61.9	+22.1
	none	P.F.D.	63.4	61.9	-2.4

The columns required to replace one line of mechanical cells were scaled up using the P.F.D. model and data from the laboratory column. Industrial column scale up is summarized in Table 4.7. A constraint of a maximum column diameter of 3.5 m was

imposed based on current practice. Due to higher kinetics (due to producing smaller bubbles), the columns incorporating sparger A were smaller in size than the columns using sparger B (or the variable gap sparger). When sparger B is used the feed throughput must be reduced and extra columns added (if the maximum diameter of 3.5 m is respected). Determination of the rate constant is presented in Appendix F.

From Table 4.7 it is evident that packing is not required when sparger A is used (column dimensions are equivalent with or without packing). Packing is necessary when sparger B (or variable gap) or no sparger are used. In this case packing dampened the axial mixing and fewer columns were required.

Table 4.7 Summary of industrial columns.

column	sparger	# of columns	height (m)	diameter (m)
open	A	1	12	2.65
	A	2	12	1.78
	B	4	16	3.18
packed	A	1	12	2.70
	A	2	12	1.80
	B	3	16	2.82
	none	3	16	2.83

Chapter 5: Conclusions and Recommendations

5.1 Conclusions

Selected operating conditions in the open and packed laboratory-scale columns were identified and are summarized in Table 4.1. During the determination of the operating conditions it was found that wash water is essential for producing a froth with sparger B but not with sparger A. The conclusions from the laboratory-scale comparison tests are as follows:

- sparger A in the open and packed columns produced the highest flotation efficiencies and equaled the flotation efficiency of the mechanical cells.
- the packed column with sparger B gave similar flotation efficiency to the mechanical cells.
- the open column with sparger B approached the efficiency of the mechanical cells.
- the packed column with no sparger gave the poorest flotation efficiency.
- the organic loss from all laboratory column configurations was less than 2% (i.e. 98% yield).

The conclusions from the pilot-scale comparative work are as follows:

- the variable gap sparger in the pilot column was incapable of matching the flotation efficiency of the mechanical cells.
- the packed column produced higher flotation efficiencies than the open column.

• the open column with the variable gap sparger and the packed column with no sparger had equivalent flotation efficiencies.

• the organic loss from all pilot column configurations was less than 3% (i.e. 97% yield).

The following conclusions were made from the alternative flotation evaluation techniques:

• a relationship between flotation efficiency and bubble surface area generation rate exists.

• sparger B produced lower surface area generation rates (hence lower flotation efficiencies) than sparger A.

• the maximum flotation efficiency was found (by interpolation) to occur at a surface area generation rate of approximately 35 s^{-1}.

• the average surface area generation rates in the open and packed pilot columns were found to be 22.6 and 23.9 s^{-1}, which helps explain why the pilot columns could not match the flotation efficiencies of the laboratory columns.

The scale up procedure was evaluated using data from the laboratory columns and pilot column dimensions. It appears that the plug flow dispersion model is more appropriate than the plug flow model for scale up. Using data from the laboratory columns, industrial-scale columns were designed. The dimensions of the industrial columns are summarized in Table 4.7. The conclusions from the industrial column scale up are as follows:

• columns incorporating sparger A are smaller than those with sparger B due to faster flotation.

• packing is not required when sparger A is used.

• packing is effective in reducing mixing when sparger B or no sparger are used.

5.2 Recommendations

Spargers were found to have the greatest effect on flotation deinking. Therefore, it is recommended to find spargers that will maximize flotation efficiency while minimizing the bubble surface area rate. The advantage of this approach is that it may lead to sparger porosities larger than the current industrial standard of 0.5 μm with less likelihood of blockage.

Pilot-scale experiments should be performed using commercial porous spargers to ensure that flotation efficiencies of 80% or higher can be obtained.

The maximum flotation efficiency obtained by the mechanical cells and the columns in this work was approximately 80%. To determine whether higher flotation efficiencies are possible, a flotation column using sparger A could be placed in series with the mechanical cells to process the plant accepts.

Consistency was one variable which could not be controlled during the experiments at Avenor. In column flotation wash water is added and the accepts are diluted. The feed and accepts consistencies for all experiments were approximately 1.2 and 0.9% respectively. It may be possible to process higher consistencies (1.8-2.0%) using flotation columns given that wash water acts to dilute the column contents.

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Appendix A

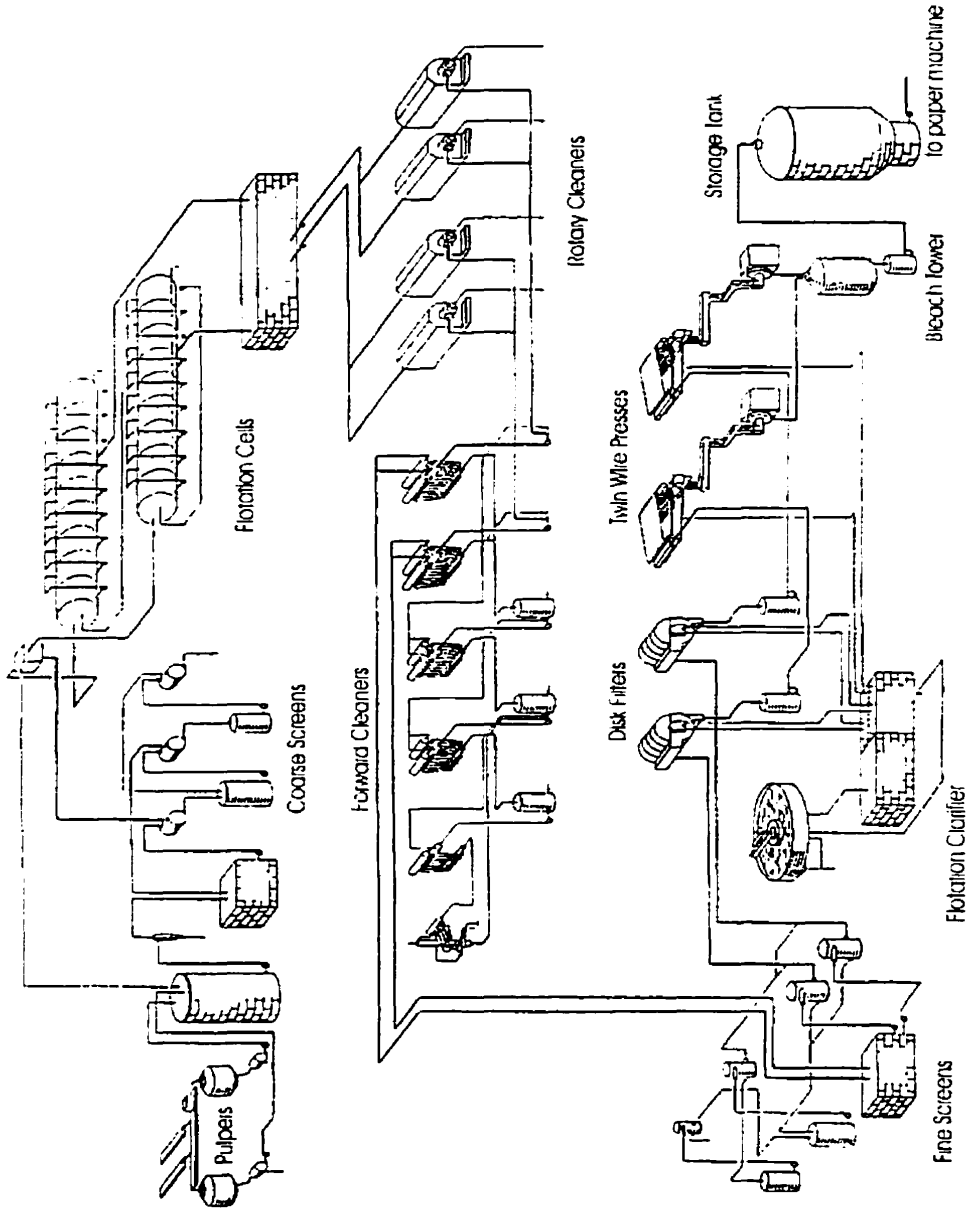


Fig. A.1 Flowsheet of Avenor's deinking plant.

Appendix B

Table B.1 Test conditions for open laboratory-scale column.

test #	superficial velocity (cm/s)						level (cm)	τ (min)	ε_g (%)
	gas	feed	w. water	accepts	rejects	bias			
openA-1	2.00	0.55	0.22	0.64	0.17	0.05	53.0	5.88	34.62
openA-2	4.00	0.72	0.22	0.65	0.30	-0.08	40.0	7.00	24.57
openA-3	1.00	0.61	0.22	0.83	0.02	0.20	50.0	5.92	15.89
openA-4	3.00	0.77	0.22	0.65	0.25	-0.03	48.0	6.83	24.30
openA-5	1.50	0.66	0.22	0.83	0.05	0.17	51.0	5.43	22.93
openA-6	1.50	1.34	0.22	1.46	0.11	0.11	54.0	2.57	34.83
openA-7	1.50	0.73	0.22	0.87	0.13	0.09	50.0	4.59	31.46
openA-8	1.50	0.39	0.22	0.49	0.15	0.07	50.0	8.48	29.33
openA-9	1.50	1.00	0.22	1.10	0.13	0.09	53.0	3.55	32.28
openA-10	1.50	0.59	0.22	0.67	0.14	0.08	48.0	6.10	30.31
openA-11	1.50	0.70	0.22	0.80	0.08	0.14	77.0	4.43	34.50
openA-12	1.50	0.73	0.22	0.89	0.09	0.13	43.0	5.19	22.59
openA-13	1.50	0.80	0.22	0.95	0.11	0.11	20.0	5.26	20.89
openA-14	1.50	0.65	0.22	0.84	0.06	0.16	55.0	5.44	20.81
openA-15	1.50	0.56	0.36	0.83	0.09	0.27	56.0	5.43	21.76
openA-16	1.50	0.79	0.08	0.82	0.03	0.05	50.0	5.80	18.10
openA-17	1.50	0.85	0.00	0.83	0.01	-0.01	51.0	5.84	16.87
openB-1	2.00	0.68	0.24	0.90	0.01	0.23	50.0	6.02	7.28
openB-2	1.00	0.68	0.24	0.90	0.01	0.23	50.0	6.19	4.06
openB-3	4.03	0.76	0.24	0.93	0.04	0.20	50.0	5.48	12.97
openB-4	4.99	0.80	0.24	0.95	0.09	0.15	50.0	5.22	15.17
openB-5	3.10	0.71	0.24	0.93	0.04	0.20	50.0	5.51	11.71
openB-6	2.00	1.52	0.24	1.69	0.01	0.23	50.0	3.15	8.87
openB-7	2.00	0.77	0.24	0.99	0.01	0.23	50.0	5.42	8.31
openB-8	2.00	0.36	0.24	0.59	0.01	0.23	50.0	8.98	9.02
openB-9	2.00	1.31	0.24	1.55	0.02	0.22	50.0	3.47	8.02
openB-10	2.00	0.69	0.24	0.89	0.02	0.22	50.0	6.04	7.79
openB-11	2.00	0.27	0.24	0.45	0.02	0.22	50.0	11.73	8.62
openB-12	2.00	0.98	0.24	1.13	0.02	0.22	50.0	4.76	7.80
openB-13	2.00	0.45	0.24	0.67	0.02	0.22	50.0	7.97	7.86

Table B.2 Test conditions for packed laboratory-scale column.

test #	superficial velocity (cm/s)						level (cm)	τ (min)	ε_g (%)
	gas	feed	w. water	accepts	rejects	bias			
packA-1	2.00	0.70	0.22	0.81	0.17	0.05	60.0	5.98	14.26
packA-2	2.50	0.97	0.22	0.82	0.29	-0.07	63.0	5.41	21.35
packA-3	1.00	0.73	0.22	0.83	0.06	0.16	63.0	6.08	10.20
packA-4	0.50	0.71	0.22	0.84	0.04	0.18	60.0	6.54	3.38
packB-1	2.00	0.46	0.22	0.62	0.04	0.18	57.0	8.33	9.19
packB-2	4.00	0.43	0.22	0.60	0.08	0.14	58.0	8.10	14.59
packB-3	1.00	0.41	0.22	0.64	0.01	0.21	57.0	8.54	4.80
packB-4	3.00	0.45	0.22	0.61	0.05	0.17	57.0	8.24	11.84
packB-5	5.00	0.51	0.22	0.64	0.07	0.15	58.0	7.54	15.78
packB-6	3.00	0.87	0.23	0.99	0.07	0.16	58.0	5.00	13.14
packB-7	3.00	0.44	0.23	0.55	0.09	0.14	58.0	9.08	12.14
packB-8	3.00	1.32	0.23	1.46	0.04	0.19	58.0	3.40	12.63
packB-9	3.00	0.30	0.23	0.43	0.11	0.12	57.0	11.74	12.34
packB-10	3.00	0.53	0.23	0.68	0.06	0.17	58.0	7.32	12.18
packNO-1	2.00	0.43	0.22	0.70	0.02	0.20	58.0	7.44	8.05
packNO-2	4.00	0.52	0.22	0.68	0.06	0.16	60.0	7.15	13.72
packNO-3	3.00	0.50	0.22	0.69	0.04	0.18	59.0	7.30	10.89
packNO-4	5.00	0.50	0.22	0.69	0.08	0.14	59.0	6.93	16.00
packNO-5	4.00	0.73	0.22	0.94	0.05	0.17	55.0	5.31	13.13
packNO-6	4.00	0.46	0.22	0.58	0.06	0.16	63.0	8.37	13.22
packNO-7	4.00	1.23	0.22	1.40	0.04	0.18	63.0	3.48	13.68
packNO-8	4.00	0.52	0.22	0.69	0.06	0.16	62.0	7.12	13.07
packNO-9	4.00	0.25	0.22	0.42	0.07	0.15	63.0	11.60	13.28

Table B.3a Test conditions for comparative work in laboratory-scale column.

test #	superficial velocity (cm/s)						level (cm)	τ (min)	ε_g (%)
	gas	feed	w. water	accepts	rejects	bias			
openA-18	1.50	0.57	0.22	0.79	0.06	0.16	62.0	5.65	20.96
openA-19	1.50	0.57	0.22	0.75	0.06	0.16	62.0	5.96	20.92
openA-20	1.50	0.57	0.22	0.75	0.05	0.17	62.0	5.96	20.42
openA-21	1.50	0.57	0.22	0.75	0.06	0.16	62.0	6.00	20.60
openB-14	3.00	0.50	0.22	0.68	0.04	0.18	60.0	7.53	10.27
openB-15	3.00	0.41	0.22	0.67	0.04	0.18	60.0	7.54	10.83
openB-16	3.00	0.51	0.22	0.67	0.04	0.18	60.0	7.51	11.02
openB-17	3.00	0.50	0.22	0.68	0.05	0.17	60.0	7.39	11.33
openB-18	3.00	0.54	0.22	0.64	0.08	0.14	58.0	7.87	11.71
openB-19	3.00	0.55	0.22	0.63	0.07	0.15	58.0	8.05	10.95
openB-20	3.00	0.59	0.22	0.60	0.06	0.16	58.0	8.44	10.69
openB-21	3.00	0.47	0.22	0.60	0.07	0.15	58.0	8.52	11.03
packA-5	2.00	0.52	0.22	0.68	0.07	0.15	56.0	6.62	20.92

Table B.3b Continuation from Table B.3a.

test #	superficial velocity (cm/s)						level (cm)	τ (min)	ε_g (%)
	gas	feed	w. water	accepts	rejects	bias			
packA-6	2.00	0.51	0.22	0.68	0.06	0.16	56.0	6.63	21.27
packA-7	2.00	0.52	0.22	0.68	0.06	0.16	56.0	6.69	21.19
packA-8	2.00	0.53	0.22	0.69	0.05	0.17	56.0	6.55	21.30
packB-11	3.00	0.73	0.22	0.64	0.05	0.17	63.0	7.65	13.46
packB-12	3.00	0.54	0.22	0.66	0.05	0.17	63.0	7.38	12.95
packB-13	3.00	0.50	0.22	0.69	0.05	0.17	63.0	7.15	12.69
packB-14	3.00	0.52	0.22	0.67	0.04	0.18	63.0	7.30	12.50
packB-15	3.00	0.52	0.22	0.61	0.07	0.15	62.0	8.02	13.06
packB-16	3.00	0.54	0.22	0.62	0.07	0.15	62.0	7.85	13.22
packB-17	3.00	0.48	0.22	0.60	0.07	0.15	62.0	8.14	13.16
packB-18	3.00	0.58	0.22	0.67	0.07	0.15	62.0	7.36	13.11
packNO-10	4.00	0.49	0.22	0.68	0.03	0.19	57.0	7.25	13.21
packNO-11	4.00	0.64	0.22	0.68	0.03	0.19	57.0	7.31	13.07
packNO-12	4.00	0.48	0.22	0.67	0.03	0.19	57.0	7.43	13.09
packNO-13	4.00	0.56	0.22	0.67	0.03	0.19	57.0	7.43	13.16

Table B.4 Test conditions for comparative work in pilot-scale column.

test #	Superficial velocity (cm/s)						level (cm)	τ (min)	ε_g (%)
	gas	feed	w. water	accepts	rejects	bias			
open50-1	2.94	0.39	0.16	0.43	0.004	0.15	72.12	11.18	11.25
open50-2	2.89	0.36	0.16	0.38	0.01	0.15	71.89	12.88	11.37
open50-3	3.00	0.33	0.16	0.40	0.01	0.15	66.86	12.42	11.53
open50-4	3.00	0.34	0.16	0.40	0.01	0.15	65.60	12.38	11.57
open50-5	2.90	0.38	0.16	0.40	0.00	0.15	65.24	12.33	11.91
open50-6	2.89	0.44	0.16	0.40	0.00	0.15	63.97	12.52	10.48
open50-7	2.92	0.43	0.16	0.40	0.01	0.15	64.93	12.25	11.99
open50-8	2.90	0.33	0.16	0.41	0.01	0.15	64.07	12.08	12.59
open50-9	2.86	0.33	0.16	0.41	0.01	0.15	65.12	12.05	12.35
pack50-1	2.78	0.30	0.18	0.40	0.01	0.17	56.79	12.96	10.16
pack50-2	2.75	0.38	0.18	0.37	0.01	0.17	63.52	13.83	9.16
pack50-3	2.77	0.27	0.18	0.36	0.01	0.17	58.15	14.32	10.09
pack50-4	2.73	0.30	0.18	0.39	0.02	0.17	57.46	13.27	10.60
pack50-5	2.73	0.32	0.18	0.39	0.01	0.17	60.11	12.83	11.95
pack50-6	2.74	0.30	0.18	0.38	0.01	0.17	59.91	12.96	12.61
pack50-7	2.72	0.30	0.18	0.39	0.01	0.17	59.66	12.73	11.68
pack50-8	2.79	0.27	0.17	0.33	0.01	0.16	54.21	15.34	12.34
pack50-9	2.79	0.25	0.17	0.31	0.01	0.16	53.06	16.48	13.11
pack50-10	2.74	0.33	0.17	0.34	0.01	0.16	59.85	14.30	13.30
pack50-11	2.91	0.40	0.17	0.38	0.01	0.16	59.78	12.91	13.07
pack50-12	2.84	0.36	0.17	0.38	0.01	0.16	59.71	13.06	12.60
pack50-13	3.06	0.28	0.17	0.38	0.01	0.16	60.24	12.95	14.20
pack50-14	3.08	0.32	0.17	0.40	0.01	0.16	61.02	12.15	13.42
pack50-15	3.17	0.38	0.17	0.45	0.01	0.16	61.42	10.90	13.18
pack50-16	3.11	0.38	0.17	0.45	0.02	0.15	60.07	11.00	12.99

Appendix C

Table C.1 Flotation efficiency and brightness gain results for open laboratory column.

test #	ERIC (ppm)			flotation	brightness (% ISO)		
	feed	accepts	reduction	efficiency (%)	feed	accepts	gain
openA-1	737.51	123.05	614.46	83.32	49.02	58.77	9.75
openA-2	668.92	126.16	542.76	81.14	49.62	58.60	8.98
openA-3	655.91	120.57	535.34	81.62	49.47	59.22	9.75
openA-4	773.87	118.95	654.92	84.63	48.80	58.89	10.09
openA-5	763.84	124.00	639.84	83.77	48.58	58.97	10.39
openA-6	815.96	148.61	667.35	81.79	47.62	58.82	11.20
openA-7	765.38	148.16	617.22	80.64	48.37	59.07	10.70
openA-8	835.21	146.82	688.39	82.42	48.37	58.70	10.33
openA-9	747.27	151.78	595.49	79.69	49.27	58.70	9.43
openA-10	668.81	138.54	530.27	79.29	49.10	58.43	9.33
openA-11	708.26	152.33	555.93	78.49	47.88	56.58	8.70
openA-12	707.32	149.96	557.36	78.80	47.77	56.35	8.58
openA-13	752.83	152.55	600.28	79.74	48.08	56.68	8.60
openA-14	758.01	149.32	608.69	80.30	48.14	56.58	8.44
openA-15	749.72	143.34	606.38	80.88	48.36	57.09	8.73
openA-16	697.18	145.89	551.29	79.07	48.88	57.80	8.92
openA-17	753.31	141.04	612.27	81.28	48.78	58.31	9.53
openB-1	853.50	430.15	423.35	49.60	47.64	53.43	5.79
openB-2	901.71	642.13	259.58	28.79	46.68	50.34	3.66
openB-3	847.75	292.49	555.26	65.50	47.75	55.42	7.67
openB-4	849.45	247.51	601.94	70.86	47.53	56.15	8.62
openB-5	779.55	269.20	510.35	65.47	48.05	55.28	7.23
openB-6	N/A.	N/A.	N/A.	N/A.	47.78	54.89	7.11
openB-7	767.11	301.76	465.35	60.66	48.83	55.91	7.08
openB-8	833.62	236.25	597.37	71.66	48.01	57.15	9.14
openB-9	853.30	408.18	445.12	52.16	47.58	54.77	7.19
openB-10	835.36	311.06	524.30	62.76	48.82	55.88	7.06
openB-11	849.00	285.86	563.14	66.33	47.90	56.45	8.55
openB-12	864.99	428.86	436.13	50.42	47.05	53.63	6.58
openB-13	836.31	311.31	525.00	62.78	47.88	55.72	7.84

Table C.2 Flotation efficiency and brightness gain results for packed laboratory column.

test #	ERIC (ppm)			flotation	brightness (% ISO)		
	feed	accepts	reduction	efficiency (%)	feed	accepts	gain
packA-1	1318.17	175.71	1142.46	86.67	42.18	56.27	14.09
packA-2	1294.50	168.72	1125.78	86.97	42.38	55.80	13.42
packA-3	1319.17	181.35	1137.82	86.25	42.90	56.06	13.16
packA-4	1245.17	289.83	955.34	76.72	42.90	54.64	11.74
packB-1	841.61	265.08	576.54	68.50	48.66	57.02	8.36
packB-2	749.49	201.23	548.26	73.15	49.31	58.48	9.17
packB-3	633.26	363.49	269.77	42.60	51.33	55.38	4.05
packB-4	830.35	224.27	606.08	72.99	48.52	58.23	9.71
packB-5	893.65	195.36	698.29	78.14	48.38	58.82	10.44
packB-6	819.21	254.95	564.26	68.88	47.10	56.86	9.76
packB-7	810.35	228.19	582.17	71.84	47.80	57.16	9.36
packB-8	761.30	265.23	496.07	65.16	49.70	57.45	7.75
packB-9	749.59	182.28	567.31	75.68	48.68	58.39	9.71
packB-10	863.24	316.72	546.52	63.31	46.93	55.83	8.90
packNO-1	779.98	316.73	463.25	59.39	46.79	53.01	6.22
packNO-2	882.76	200.92	681.84	77.24	45.62	54.68	9.06
packNO-3	880.06	250.84	629.22	71.50	46.21	54.39	8.18
packNO-4	846.39	206.58	639.81	75.59	46.77	55.24	8.47
packNO-5	855.65	302.52	553.13	64.64	48.28	55.61	7.33
packNO-6	882.92	230.75	652.17	73.87	47.65	57.12	9.47
packNO-7	904.69	347.06	557.63	61.64	47.14	54.86	7.72
packNO-8	851.32	232.28	619.04	72.72	48.09	56.86	8.77
packNO-9	840.49	183.66	656.83	78.15	47.83	57.41	9.58

Table C.3a Flotation efficiency and brightness gain results from the comparative work in the laboratory column.

test #	ERIC (ppm)			flotation	brightness (% ISO)		
	feed	accepts	reduction	efficiency (%)	feed	accepts	gain
openA-18	838.95	160.66	678.29	80.85	46.37	57.53	11.16
openA-19	922.38	164.88	757.50	82.12	46.23	57.55	11.32
openA-20	928.25	165.96	762.29	82.12	46.42	57.49	11.07
openA-21	801.86	145.32	656.54	81.88	47.31	58.26	10.95
openB-14	894.23	249.89	644.34	72.06	45.30	55.54	10.24
openB-15	867.81	249.28	618.53	71.27	45.34	55.55	10.21
openB-16	822.06	236.60	585.46	71.22	46.61	55.70	9.09

Table C.3b Continuation from Table C.3a.

test #	ERIC (ppm)			flotation	brightness (% ISO)		
	feed	accepts	reduction	efficiency (%)	feed	accepts	gain
openB-17	886.34	224.48	661.86	74.67	46.26	56.36	10.10
openB-18	826.17	197.81	628.36	76.06	45.98	55.74	9.76
openB-19	965.06	221.95	743.11	77.00	44.60	55.14	10.54
openB-20	902.45	234.45	668.00	74.02	45.43	56.05	10.62
openB-21	986.25	227.85	758.40	76.90	45.17	57.08	11.91
packA-5	861.91	181.03	680.88	79.00	45.84	57.53	11.69
packA-6	860.39	174.08	686.31	79.77	47.31	58.22	10.91
packA-7	909.02	179.45	729.57	80.26	45.62	58.09	12.47
packA-8	829.11	160.22	668.89	80.68	47.28	57.55	10.27
packB-11	1000.98	226.96	774.02	77.33	46.58	57.21	10.63
packB-12	903.15	179.80	723.35	80.09	47.05	58.02	10.97
packB-13	824.93	162.54	662.39	80.30	47.89	58.39	10.50
packB-14	876.24	168.74	707.50	80.74	49.00	57.83	8.83
packB-15	883.33	213.69	669.64	75.81	46.98	56.79	9.81
packB-16	939.56	215.88	723.68	77.02	46.20	56.34	10.14
packB-17	966.34	228.35	737.99	76.37	45.92	56.04	10.12
packB-18	942.38	237.23	705.15	74.83	46.72	56.15	9.43
packNO-10	834.72	230.48	604.24	72.39	47.54	56.26	8.72
packNO-11	851.00	239.71	611.29	71.83	47.61	56.82	9.21
packNO-12	844.94	216.92	628.02	74.33	47.16	57.49	10.33
packNO-13	871.57	220.66	650.91	74.68	47.30	57.61	10.31
cells-1	838.95	181.18	657.77	78.40	46.37	57.31	10.94
cells-2	922.38	196.83	725.55	78.66	46.23	56.88	10.65
cells-3	928.25	179.18	749.07	80.70	46.42	57.33	10.91
cells-4	801.86	169.36	632.50	78.88	47.31	57.72	10.41
cells-5	883.33	201.31	682.02	77.21	46.98	56.99	10.01
cells-6	939.56	216.57	722.99	76.95	46.20	56.43	10.23
cells-7	966.34	220.91	745.43	77.14	45.92	55.90	9.98
cells-8	942.38	208.17	734.21	77.91	46.72	56.82	10.10

Table C.4 Flotation efficiency results from the comparative work in the pilot column.

	ERIC (ppm)			flotation	plant flotation	brightness (% ISO)				
test #	feed	accepts	plant acc.	eff. (%)	eff. (%)	feed	accepts	plant acc.	Gain	plant gain
open50-1	964.80	384.78	-	60.12	-	46.27	54.46	-	8.19	-
open50-2	1020.94	254.96	-	75.03	-	47.24	57.09	-	9.85	-
open50-3	914.50	346.74	177.30	62.08	80.61	48.53	55.95	58.99	7.42	10.46
open50-4	900.51	324.20	195.55	64.00	78.28	48.83	57.19	59.70	8.36	10.87
open50-5	888.66	248.48	166.03	72.04	81.32	48.37	58.51	58.97	10.14	10.60
open50-6	770.97	279.12	162.58	63.80	78.91	49.73	56.84	59.45	7.11	9.72
open50-7	834.50	289.33	150.63	65.33	81.95	50.07	57.73	61.45	7.66	11.38
open50-8	835.68	268.41	203.97	67.88	75.59	49.86	58.76	60.56	8.90	10.70
open50-9	932.89	353.40	221.33	62.12	76.27	48.58	56.91	59.08	8.33	10.50
pack50-1	926.66	259.81	173.65	71.96	81.26	48.27	58.34	60.15	10.07	11.88
pack50-2	939.79	249.87	168.09	73.41	82.11	48.27	58.91	60.72	10.64	12.45
pack50-3	964.35	254.82	200.59	73.58	79.20	47.32	58.16	59.45	10.84	12.13
pack50-4	1070.45	301.81	205.28	71.81	80.82	47.08	57.62	59.25	10.54	12.17
pack50-5	843.25	255.00	183.94	69.76	78.19	47.72	58.57	60.15	10.85	12.43
pack50-6	984.00	269.83	173.57	72.58	82.36	47.61	57.65	58.82	10.04	11.21
pack50-7	723.41	223.85	182.11	69.06	74.83	50.41	59.48	60.39	9.07	9.98
pack50-8	938.89	210.49	163.54	77.58	82.58	47.25	59.07	60.01	11.82	12.76
pack50-9	862.60	213.44	163.40	75.26	81.06	49.52	60.07	61.51	10.55	11.99
pack50-10	869.57	208.94	155.56	75.97	82.11	49.39	60.32	61.70	10.93	12.31
pack50-11	836.42	234.11	155.81	72.01	81.37	50.01	60.11	62.20	10.10	12.19
pack50-12	893.97	257.27	177.49	71.22	80.15	48.78	59.29	61.55	10.51	12.77
pack50-13	858.48	270.06	184.51	68.54	78.51	48.78	59.02	60.96	10.24	12.18
pack50-14	924.87	298.45	193.82	67.73	79.04	48.57	58.02	60.41	9.45	11.84
pack50-15	920.03	282.34	166.97	69.31	81.85	48.27	58.73	60.85	10.46	12.58
pack50-16	929.19	348.51	172.61	62.49	81.42	47.85	56.25	59.94	8.40	12.09

Appendix D

Table D.1 Consistency and ash data for tests performed in open laboratory-scale column.

	consistency (%)			ash content (%)		
test =	feed	accepts	rejects	feed	accepts	rejects
openA-1	1.14	0.98	0.33	11.37	7.45	54.09
openA-2	1.23	1.20	0.41	11.95	7.74	31.79
openA-3	1.22	0.83	1.99	11.46	8.82	52.06
openA-4	1.26	1.17	0.34	11.08	8.09	41.17
openA-5	1.24	0.89	1.31	10.51	7.84	53.20
openA-6	1.28	1.14	0.77	13.80	10.61	50.66
openA-7	1.23	1.03	0.42	12.50	10.11	50.98
openA-8	1.28	0.84	0.27	12.50	8.89	50.90
openA-9	1.32	1.13	0.53	11.38	9.14	47.54
openA-10	1.26	0.97	0.35	11.24	7.81	48.60
openA-11	1.14	0.87	0.51	11.74	8.35	54.45
openA-12	1.13	0.85	0.41	11.67	8.16	53.58
openA-13	1.13	0.90	0.47	10.80	8.54	50.03
openA-14	1.15	0.83	0.67	11.25	8.33	50.96
openA-15	1.14	0.73	0.41	10.78	7.58	51.99
openA-16	1.15	1.00	1.57	11.11	8.78	46.95
openA-17	1.12	1.02	3.91	10.90	8.74	43.79
openB-1	1.20	0.87	1.07	10.40	9.08	47.93
openB-2	1.16	0.88	0.35	9.63	10.40	44.70
openB-3	1.20	0.91	0.70	9.94	7.88	48.72
openB-4	1.18	0.92	0.54	10.24	7.85	46.74
openB-5	1.20	0.88	0.57	9.69	8.36	48.58
openB-6	1.19	0.96	3.47	11.04	10.79	37.84
openB-7	1.16	0.87	4.19	11.92	11.29	41.16
openB-8	1.14	0.68	3.58	11.51	9.60	43.94
openB-9	1.21	0.97	2.48	12.61	12.55	43.34
openB-10	1.15	0.80	4.20	11.67	10.96	45.83
openB-11	1.21	0.64	3.62	11.97	10.25	47.11
openB-12	1.20	0.96	1.80	12.15	10.87	43.81
openB-13	1.25	0.78	1.13	11.76	10.17	46.02

Table D.2 Pulp flowrate and standard deviation data for tests performed in open laboratory-scale column.

	pulp flowrate (ml/s)				std. dev. of pulp flowrate (ml/s)			
test #	feed	w. water	accepts	rejects	feed	w. water	accepts	rejects
openA-1	43.82	17.63	51.48	13.62	14.01	1.76	2.01	2.04
openA-2	58.03	17.63	51.80	24.04	26.54	1.76	1.85	3.61
openA-3	48.49	17.63	66.43	1.60	7.20	1.76	1.72	0.24
openA-4	61.95	17.63	52.08	20.03	28.24	1.76	2.09	3.00
openA-5	52.74	17.63	66.14	4.01	6.57	1.76	1.45	0.60
openA-6	107.33	17.63	116.95	8.81	11.74	1.76	4.28	1.32
openA-7	58.85	17.63	69.71	10.42	6.64	1.76	1.41	1.56
openA-8	31.52	17.63	38.95	12.02	11.27	1.76	1.40	1.80
openA-9	80.50	17.63	88.39	10.42	10.77	1.76	1.97	1.56
openA-10	47.00	17.63	53.73	11.22	8.05	1.76	1.88	1.68
openA-11	55.71	17.63	63.74	6.41	10.09	1.76	2.25	0.96
openA-12	58.47	17.63	71.05	7.21	2.17	1.76	1.67	1.08
openA-13	64.37	17.63	76.32	8.81	8.89	1.76	5.09	1.32
openA-14	52.46	17.63	67.06	4.81	3.23	1.76	1.32	0.72
openA-15	44.94	28.84	66.20	7.21	3.61	2.88	1.56	1.08
openA-16	62.92	6.41	66.01	2.40	6.16	0.64	1.44	0.36
openA-17	68.01	0.00	66.36	0.80	3.85	0.00	1.65	0.12
openB-1	54.32	19.23	72.02	0.80	2.59	1.92	2.19	0.12
openB-2	54.63	19.23	72.45	0.80	1.78	1.92	1.32	0.12
openB-3	60.65	19.23	74.26	3.20	5.80	1.92	3.98	0.48
openB-4	63.81	19.23	75.95	7.21	4.83	1.92	4.70	1.08
openB-5	56.85	19.23	74.89	3.20	3.40	1.92	4.36	0.48
openB-6	121.42	19.23	135.15	0.80	8.83	1.92	2.86	0.12
openB-7	61.51	19.23	79.01	0.80	4.86	1.92	3.37	0.12
openB-8	29.09	19.23	47.37	0.80	2.53	1.92	2.95	0.12
openB-9	104.64	19.23	124.06	1.60	8.74	1.92	14.78	0.24
openB-10	55.49	19.23	71.31	1.60	2.08	1.92	1.61	0.24
openB-11	21.38	19.23	36.41	1.60	3.59	1.92	11.29	0.24
openB-12	78.69	19.23	90.51	1.60	6.34	1.92	1.57	0.24
openB-13	36.42	19.23	54.06	1.60	9.44	1.92	1.96	0.24

Table D.3 Corrected pulp flowrate data and organic loss results for tests performed in open laboratory-scale column.

test #	corrected pulp flowrate (ml/s)				organic loss (%)
	feed	w. water	accepts	rejects	
openA-1	47.1	17.8	51.4	13.6	4.27
openA-2	53.9	18.5	52.1	20.3	9.75
openA-3	50.5	17.7	66.4	1.9	3.32
openA-4	50.2	18.6	51.7	17.1	6.06
openA-5	52.1	17.7	66.1	3.8	4.01
openA-6	107.5	17.9	116.6	8.8	2.80
openA-7	61.3	18.2	69.8	9.7	3.02
openA-8	33.8	17.6	39.1	12.4	4.37
openA-9	78.1	18.6	87.3	9.3	2.83
openA-10	47.0	17.7	53.7	11.0	3.74
openA-11	52.9	17.7	63.8	6.7	2.95
openA-12	59.2	18.1	70.6	6.7	2.15
openA-13	60.2	17.2	67.9	8.8	3.39
openA-14	50.3	18.2	66.8	4.5	2.88
openA-15	44.9	28.8	66.2	7.5	3.21
openA-16	68.2	6.4	65.9	2.8	3.34
openA-17	67.4	0.0	66.2	1.1	3.59
openB-1	54.2	19.1	72.2	1.2	1.14
openB-2	54.4	18.8	72.6	0.6	0.20
openB-3	59.1	19.1	74.9	3.3	1.85
openB-4	63.8	19.2	76.1	6.9	2.93
openB-5	57.5	19.5	73.6	3.4	1.59
openB-6	118.0	19.0	135.8	1.2	2.06
openB-7	61.3	19.1	79.5	0.8	3.14
openB-8	29.1	19.3	47.3	1.1	7.50
openB-9	104.7	19.3	122.6	1.4	1.77
openB-10	54.3	18.6	71.7	1.2	4.94
openB-11	21.4	19.2	38.8	1.8	15.09
openB-12	73.3	18.8	90.8	1.3	1.70
openB-13	36.5	19.3	54.0	1.8	2.72

Table D.4 Consistency and ash data for tests performed in packed laboratory-scale column.

test #	consistency (%)			ash content (%)		
	feed	accepts	rejects	feed	accepts	rejects
packA-1	1.03	0.76	0.40	14.59	9.57	55.20
packA-2	1.02	0.80	0.45	14.51	9.29	54.35
packA-3	0.98	0.66	0.72	14.80	10.43	55.19
packA-4	0.97	0.68	0.15	13.57	11.47	48.35
packB-1	1.10	0.70	0.38	10.71	8.77	50.55
packB-2	1.30	0.82	0.39	12.63	9.16	54.44
packB-3	0.91	0.60	0.21	11.07	11.80	48.70
packB-4	1.26	0.85	0.40	11.67	10.24	50.04
packB-5	1.34	0.91	0.48	12.42	9.38	50.99
packB-6	1.28	0.87	0.52	12.68	10.49	52.44
packB-7	1.34	0.92	0.29	12.97	9.43	46.90
packB-8	1.20	1.05	1.13	12.42	11.34	44.73
packB-9	1.30	0.88	0.19	12.35	8.85	51.17
packB-10	1.29	0.93	0.32	10.70	9.60	49.24
packNO-1	1.34	0.85	0.35	11.25	9.49	41.37
packNO-2	1.17	0.78	0.34	11.46	9.44	48.52
packNO-3	1.24	0.82	0.29	10.88	9.33	46.32
packNO-4	1.24	0.87	0.35	10.75	8.88	47.09
packNO-5	1.36	1.04	0.64	10.94	9.69	47.25
packNO-6	1.33	0.93	0.35	11.43	9.22	50.22
packNO-7	1.38	1.08	1.00	11.12	10.23	41.75
packNO-8	1.33	0.92	0.45	10.30	8.66	46.44
packNO-9	1.31	0.76	0.19	9.91	8.04	48.90

Table D.5a Pulp flowrate and standard deviation data for tests performed in packed laboratory-scale column.

test #	pulp flowrate (ml/s)				std. dev. of pulp flowrate (ml/s)			
	feed	w. water	accepts	rejects	feed	w. water	accepts	rejects
packA-1	55.92	17.63	65.07	13.34	5.83	1.76	1.58	2.00
packA-2	77.40	17.63	65.40	23.19	7.96	1.76	2.00	3.48
packA-3	58.12	17.63	66.49	4.54	2.64	1.76	1.34	0.68
packA-4	57.21	17.63	67.03	2.90	4.07	1.76	1.35	0.43
packB-1	36.68	17.63	49.93	3.28	12.13	1.76	3.42	0.49
packB-2	34.73	17.63	48.15	6.14	11.26	1.76	2.65	0.92
packB-3	32.99	17.63	51.03	0.51	7.12	1.76	1.78	0.08
packB-4	35.97	17.63	48.98	3.88	14.08	1.76	4.09	0.58
packB-5	41.23	17.63	51.04	5.83	11.51	1.76	2.03	0.87
packB-6	69.50	18.43	79.32	5.50	3.96	1.84	4.23	0.82
packB-7	35.28	18.43	44.18	7.28	13.86	1.84	5.54	1.09
packB-8	105.98	18.43	117.33	3.36	8.42	1.84	12.69	0.50
packB-9	24.43	18.43	34.19	8.97	2.37	1.84	6.57	1.35
packB-10	42.50	18.43	54.78	5.14	3.30	1.84	2.13	0.77

Table D.5b Continuation from Table D.5a.

test #	pulp flowrate (ml/s)				std. dev. of pulp flowrate (ml/s)			
	feed	w.water	accepts	rejects	feed	w.water	accepts	rejects
packNO-1	34.18	17.63	56.45	1.34	5.80	1.76	3.08	0.20
packNO-2	41.36	17.63	54.81	4.65	10.37	1.76	3.64	0.70
packNO-3	40.42	17.63	55.57	3.38	9.29	1.76	4.31	0.51
packNO-4	40.06	17.63	55.20	6.21	6.84	1.76	3.22	0.93
packNO-5	58.60	17.63	75.35	3.80	8.01	1.76	4.48	0.57
packNO-6	36.84	17.63	46.65	5.06	11.41	1.76	2.51	0.76
packNO-7	98.21	17.63	111.78	3.09	12.27	1.76	12.69	0.46
packNO-8	41.45	17.63	55.07	4.59	3.38	1.76	2.83	0.69
packNO-9	20.38	17.63	33.63	6.00	1.56	1.76	4.05	0.90

Table D.6 Corrected pulp flowrate data and organic loss results for tests performed in packed laboratory-scale column.

test #	Corrected pulp flowrate (ml/s)				organic loss
	feed	w. water	accepts	rejects	(%)
packA-1	59.8	17.9	64.8	12.9	4.44
packA-2	72.7	17.3	65.8	24.3	7.88
packA-3	55.3	16.5	67.1	4.7	3.29
packA-4	53.4	17.0	67.4	2.9	0.51
packB-1	35.4	17.7	49.8	3.3	1.78
packB-2	37.0	17.5	48.4	6.2	2.60
packB-3	34.3	17.4	51.3	0.5	0.20
packB-4	35.9	17.5	49.5	3.9	1.96
packB-5	38.9	17.8	50.9	5.8	2.95
packB-6	67.5	18.3	80.2	5.5	1.78
packB-7	33.8	18.4	44.9	7.3	2.83
packB-8	105.8	18.4	120.8	3.4	1.90
packB-9	24.4	18.5	33.9	9.0	3.02
packB-10	41.7	18.3	54.9	5.2	1.76
packNO-1	38.8	18.0	55.4	1.3	0.58
packNO-2	41.4	17.7	54.5	4.6	1.88
packNO-3	41.4	17.6	55.6	3.4	1.16
packNO-4	43.2	17.8	54.8	6.2	2.40
packNO-5	59.6	18.4	74.2	3.7	1.71
packNO-6	34.4	17.5	46.9	5.1	2.20
packNO-7	98.1	17.6	112.7	3.1	1.50
packNO-8	41.9	17.7	55.0	4.6	2.22
packNO-9	20.4	17.9	32.4	5.9	2.36

Table D.7 Consistency and ash data for the comparative work in the laboratory-scale column.

test #	consistency (%)			ash content (%)		
	feed	accepts	rejects	feed	accepts	rejects
openA-18	1.35	0.97	0.37	11.19	8.18	53.18
openA-19	1.36	0.97	0.40	11.10	8.15	54.01
openA-20	1.23	0.92	0.43	10.57	8.59	51.56
openA-21	1.28	0.90	0.36	10.09	8.34	51.07
openB-14	1.32	0.89	0.38	11.73	9.90	49.05
openB-15	1.33	0.90	0.39	11.16	9.73	48.58
openB-16	1.34	0.92	0.28	10.32	8.94	47.76
openB-17	1.36	0.91	0.32	9.87	8.63	46.24
openB-18	1.30	0.81	0.17	11.60	9.16	49.50
openB-19	1.36	0.92	0.31	12.24	10.16	47.78
openB-20	1.42	0.99	0.45	12.66	10.05	52.55
openB-21	1.42	0.93	0.42	13.72	10.62	53.25
packA-5	1.38	0.94	0.37	11.17	8.98	52.32
packA-6	1.38	0.89	0.39	12.36	9.74	55.13
packA-7	1.34	0.96	0.37	11.86	12.02	54.41
packA-8	1.37	0.96	0.43	12.09	8.97	53.18
packB-11	1.28	0.86	0.22	10.72	9.68	45.49
packB-12	1.34	0.90	0.23	11.02	9.31	45.62
packB-13	1.31	0.88	0.18	10.29	9.57	44.32
packB-14	1.30	0.91	0.16	9.23	8.86	42.89
packB-15	1.44	0.94	0.31	9.60	8.09	44.39
packB-16	1.31	0.92	0.25	8.91	7.37	45.69
packB-17	1.40	0.93	0.29	8.55	7.38	46.82
packB-18	1.44	0.95	0.30	9.04	7.48	45.01
packNO-10	1.34	0.88	0.18	11.19	9.75	44.62
packNO-11	1.36	0.89	0.20	11.02	10.13	44.19
packNO-12	1.32	0.88	0.22	11.57	10.19	45.07
packNO-13	1.34	0.88	0.21	11.59	10.47	45.26

Table D.8a Pulp flowrate and standard deviation data for the comparative work in the laboratory-scale column.

test #	pulp flowrate (ml/s)				std. dev. of pulp flowrate (ml/s)			
	feed	w. water	accepts	rejects	feed	w. water	accepts	rejects
openA-18	45.94	17.63	63.10	4.72	3.11	1.76	2.97	0.71
openA-19	46.01	17.63	59.84	5.19	2.94	1.76	4.23	0.78
openA-20	46.00	17.63	60.27	4.03	3.46	1.76	3.86	0.60
openA-21	45.88	17.63	59.75	4.93	2.69	1.76	3.91	0.74
openB-14	40.46	17.63	54.13	3.01	18.33	1.76	6.14	0.45
openB-15	32.84	17.63	53.70	3.59	17.17	1.76	4.82	0.54

Table D.8b Continuation from Table D.8a.

test #	pulp flowrate (ml/s)				std. dev. of pulp flowrate (ml/s)			
	feed	w. water	accepts	rejects	feed	w. water	accepts	rejects
openB-16	40.57	17.63	53.78	3.58	14.04	1.76	4.98	0.54
openB-17	39.71	17.63	54.48	3.80	15.96	1.76	4.27	0.57
openB-18	43.25	17.63	51.21	6.55	17.36	1.76	3.96	0.98
openB-19	43.77	17.63	50.51	5.61	24.72	1.76	6.55	0.84
openB-20	47.61	17.63	48.31	4.80	20.04	1.76	4.30	0.72
openB-21	37.47	17.63	47.71	5.55	8.16	1.76	4.19	0.83
packA-5	41.51	17.63	54.83	5.54	10.74	1.76	2.85	0.83
packA-6	40.96	17.63	54.54	5.16	13.95	1.76	1.66	0.77
packA-7	41.71	17.63	54.13	5.09	15.52	1.76	1.55	0.76
packA-8	42.13	17.63	55.18	3.94	18.67	1.76	3.11	0.59
packB-11	58.29	17.63	50.89	4.12	18.89	1.76	12.05	0.62
packB-12	42.98	17.63	53.09	3.89	22.98	1.76	5.04	0.58
packB-13	40.12	17.63	54.92	3.77	25.41	1.76	2.75	0.57
packB-14	42.01	17.63	53.95	3.20	22.57	1.76	2.71	0.48
packB-15	41.35	17.63	48.90	5.30	15.79	1.76	6.45	0.80
packB-16	43.37	17.63	49.90	5.79	18.18	1.76	8.27	0.87
packB-17	38.86	17.63	48.16	5.45	15.80	1.76	5.73	0.82
packB-18	46.52	17.63	53.29	5.41	18.07	1.76	8.53	0.81
packNO-10	38.97	17.63	54.82	2.55	21.27	1.76	3.46	0.38
packNO-11	51.35	17.63	54.50	2.31	33.27	1.76	3.57	0.35
packNO-12	38.35	17.63	53.59	2.37	16.99	1.76	3.38	0.36
packNO-13	45.06	17.63	53.51	2.63	15.57	1.76	3.07	0.39

Table D.9a Corrected pulp flowrate data and organic loss results for the comparative work in the laboratory-scale column.

test #	corrected pulp flowrate (ml/s)				organic loss
	feed	w. water	accepts	rejects	(%)
openA-18	47.8	18.2	61.4	4.6	1.39
openA-19	46.1	17.8	58.8	5.2	1.69
openA-20	46.1	17.7	60.1	4.0	1.65
openA-21	46.0	17.8	58.9	4.9	1.63
openB-14	40.4	17.6	55.0	3.0	1.22
openB-15	39.7	17.6	53.7	3.6	1.51
openB-16	39.2	17.7	53.3	3.6	1.10
openB-17	41.3	17.5	55.0	3.8	1.28
openB-18	40.5	17.6	51.5	6.6	1.21
openB-19	43.5	17.3	55.1	5.7	1.79
openB-20	36.4	17.5	49.1	4.8	2.28
openB-21	35.7	17.6	47.8	5.6	2.48
packA-5	41.7	17.9	54.1	5.5	1.90
packA-6	41.8	17.8	54.4	5.1	1.78
packA-7	41.7	17.6	54.2	5.1	1.72
packA-8	41.2	17.7	55.0	3.9	1.58

Table D.9b Continuation from Table D.9a.

test #	corrected pulp flowrate (ml/s)				organic loss (%)
	feed	w. water	accepts	rejects	
packB-11	44.4	17.5	57.7	4.1	0.96
packB-12	40.6	17.5	54.2	3.9	1.00
packB-13	40.8	17.7	54.7	3.8	0.80
packB-14	39.7	17.6	54.1	3.2	0.64
packB-15	36.5	17.6	48.9	5.3	1.93
packB-16	39.6	17.6	51.4	5.8	1.63
packB-17	35.7	17.7	47.9	5.4	1.79
packB-18	42.8	17.6	54.9	5.4	1.57
packNO-10	40.0	17.6	55.0	2.6	0.55
packNO-11	39.0	17.7	54.4	2.3	0.55
packNO-12	38.3	17.6	53.6	2.4	0.65
packNO-13	38.6	17.6	53.6	2.6	0.65

Table D.10 Consistency and ash data for the comparative work in the pilot-scale column.

test #	consistency (%)			ash content (%)		
	feed	accepts	rejects	feed	accepts	rejects
open50-1	1.41	1.05	4.18	11.07	9.81	41.10
open50-2	1.40	1.00	1.99	10.60	8.78	40.10
open50-3	1.28	0.98	2.33	9.16	8.24	37.20
open50-4	1.26	0.88	2.76	8.75	7.95	39.50
open50-5	1.22	0.84	3.51	9.76	7.14	40.02
open50-6	1.27	0.92	3.04	8.48	7.40	40.00
open50-7	1.28	0.86	1.95	9.16	8.19	40.90
open50-8	1.28	0.89	1.64	8.77	8.01	39.50
open50-9	1.29	0.93	1.47	9.20	7.87	40.00
pack50-1	1.41	0.90	0.65	9.89	8.24	38.45
pack50-2	1.38	0.89	0.84	9.73	8.08	40.99
pack50-3	1.15	0.77	0.75	8.80	7.75	41.44
pack50-4	1.21	0.85	0.57	9.41	8.65	42.15
pack50-5	1.10	0.74	1.65	10.00	8.47	42.32
pack50-6	1.08	0.72	3.74	9.77	8.07	44.99
pack50-7	1.12	0.82	0.75	10.80	8.92	43.90
pack50-8	1.25	0.62	0.57	10.40	7.43	41.67
pack50-9	1.24	0.77	0.86	9.96	8.80	38.14
pack50-10	1.21	0.84	0.66	10.10	8.25	37.46
pack50-11	1.28	0.82	0.70	10.20	8.80	38.55
pack50-12	1.38	0.88	0.65	9.75	8.95	40.81
pack50-13	1.27	0.81	0.70	8.65	8.26	37.10
pack50-14	1.29	0.94	0.63	8.81	8.66	38.70
pack50-15	1.28	0.92	0.83	9.86	9.05	40.70
pack50-16	1.28	1.16	0.78	9.15	8.49	40.50

Table D.11 Pulp flowrate and standard deviation data for the comparative work in the pilot-scale column.

test #	pulp flowrate (l/min)				std. dev. of pulp flowrate (l/min)			
	feed	w. water	accepts	rejects	feed	w. water	accepts	rejects
open50-1	46.17	18.50	51.09	0.44	8.48	1.85	5.90	0.07
open50-2	41.84	18.50	44.33	0.92	7.99	1.85	0.27	0.14
open50-3	38.79	18.50	46.59	0.63	3.14	1.85	0.43	0.09
open50-4	39.58	18.50	46.91	0.70	1.92	1.85	0.40	0.11
open50-5	44.62	18.50	46.96	0.28	7.10	1.85	0.42	0.04
open50-6	51.93	18.50	47.18	0.35	7.40	1.85	0.45	0.05
open50-7	51.13	18.50	47.26	0.78	8.49	1.85	0.54	0.12
open50-8	38.76	18.50	47.71	0.68	2.24	1.85	0.42	0.10
open50-9	38.50	18.50	47.84	0.76	2.46	1.85	0.28	0.11
pack50-1	35.08	21.60	46.71	1.12	2.73	2.16	1.11	0.17
pack50-2	44.62	21.60	43.39	1.06	10.95	2.16	4.23	0.16
pack50-3	31.55	21.60	42.14	1.69	2.32	2.16	2.90	0.25
pack50-4	34.73	21.60	45.31	1.79	2.26	2.16	1.51	0.27
pack50-5	37.37	21.60	45.79	1.50	2.64	2.16	0.20	0.22
pack50-6	35.54	21.60	45.03	1.37	1.85	2.16	0.28	0.21
pack50-7	35.17	21.60	46.36	1.66	2.56	2.16	0.27	0.25
pack50-8	31.35	20.20	38.81	0.88	7.70	2.02	9.42	0.13
pack50-9	29.48	20.20	35.92	1.27	8.31	2.02	5.25	0.19
pack50-10	39.22	20.20	40.48	1.45	7.47	2.02	2.13	0.22
pack50-11	47.27	20.20	44.99	1.11	5.95	2.02	0.29	0.17
pack50-12	42.26	20.20	44.72	1.64	6.96	2.02	0.51	0.25
pack50-13	32.51	20.20	44.22	1.52	1.99	2.02	0.18	0.23
pack50-14	37.36	20.20	47.43	0.95	6.94	2.02	4.08	0.14
pack50-15	44.61	20.20	52.93	1.58	3.41	2.02	2.15	0.24
pack50-16	44.40	20.20	52.77	2.10	4.15	2.02	4.76	0.32

Table D.12a Corrected pulp flowrate data and organic loss results for the comparative work in the pilot-scale column.

test #	corrected pulp flowrate (ml/s)				organic loss (%)
	feed	w. water	accepts	rejects	
open50-1	38.4	16.6	54.5	0.5	2.54
open50-2	29.9	15.6	44.3	1.1	3.49
open50-3	31.3	16.1	46.7	0.6	2.40
open50-4	34.4	13.5	47.1	0.7	2.94
open50-5	29.9	17.4	47.0	0.3	1.91
open50-6	30.5	17.1	47.3	0.4	2.05
open50-7	30.8	17.4	47.4	0.8	2.57
open50-8	33.7	14.9	47.9	0.7	1.75
open50-9	33.2	15.4	47.9	0.8	1.80

Table D.12b Continuation from Table D.12a.

test #	corrected pulp flowrate (ml/s)				organic loss (%)
	feed	w. water	accepts	rejects	
pack50-1	29.9	18.7	47.5	1.1	1.16
pack50-2	25.8	21.0	45.7	1.1	1.69
pack50-3	28.8	19.3	46.3	1.7	2.46
pack50-4	30.7	18.2	47.0	1.8	1.76
pack50-5	30.5	16.9	45.8	1.6	5.04
pack50-6	31.0	15.6	45.1	1.4	9.51
pack50-7	30.4	17.8	46.4	1.7	2.35
pack50-8	26.3	19.9	45.3	0.9	1.01
pack50-9	29.5	15.3	48.7	1.3	2.10
pack50-10	23.9	19.2	41.6	1.5	2.39
pack50-11	31.2	16.8	46.2	0.9	1.07
pack50-12	27.2	19.2	44.8	1.7	1.92
pack50-13	28.9	16.9	44.2	1.6	2.10
pack50-14	25.1	20.8	45.0	0.9	1.16
pack50-15	38.8	18.1	55.3	1.6	1.76
pack50-16	41.2	19.2	58.3	2.1	2.02

Table D.13 Consistency and ash data for the mechanical cells.

test #	consistency (%)			ash content (%)		
	feed	accepts	rejects	feed	accepts	rejects
cellsO-3	1.28	1.14	2.24	9.16	7.51	37.77
cellsO-5	1.22	1.06	1.46	9.76	6.60	42.30
cellsO-7	1.28	1.06	2.01	9.16	7.04	40.60
cellsO-9	1.29	1.12	2.39	9.20	7.35	40.80
cellsP-1	1.41	1.21	2.67	9.89	5.44	40.67
cellsP-3	1.15	1.00	2.55	8.80	7.28	41.50
cellsP-5	1.10	0.97	3.36	10.00	8.32	43.70
cellsP-7	1.12	0.99	4.93	10.80	8.90	47.00
cellsP-9	1.24	1.06	1.69	9.96	7.62	42.70
cellsP-11	1.28	1.04	1.89	10.20	7.61	41.64
cellsP-13	1.27	1.06	1.47	8.65	7.20	38.30
cellsP-15	1.28	1.10	3.34	9.86	7.98	39.53

Table D.14 Pulp flowrate data and organic loss results for the mechanical cells.

	pulp flowrate (l/min)		std. dev. of flowrate (l/min)		corrected flowrate (l/min)		organic
test #	feed	rejects	feed	rejects	feed	rejects	loss (%)
cellsO-3	15000	2130	325	300	15123	1960	9.18
cellsO-5	15000	2130	302	300	15245	2005	9.00
cellsO-7	15250	2130	389	300	15009	1971	8.92
cellsO-9	15393	2130	300	300	15587	1983	9.51
cellsP-1	15250	1860	357	300	14990	1745	5.96
cellsP-3	15350	1860	376	300	15261	1860	7.66
cellsP-5	15405	1860	343	300	15503	1698	7.76
cellsP-7	15041	1860	322	300	14870	1943	8.50
cellsP-9	14200	1860	432	300	14665	1887	8.28
cellsP-11	15100	1860	329	300	15083	1702	7.23
cellsP-13	15250	1860	358	300	14932	1899	9.28
cellsP-15	15000	1860	310	300	15287	1785	8.47

Appendix E

Table E.1 Bubble size and surface area generation rate data for tests performed in open laboratory-scale column.

test #	Ubt (cm/s)	db (cm)	Sb (s^{-1})
openA-1	10.34	0.08	154.16
openA-2	22.72	0.38	63.86
openA-3	8.66	0.05	109.98
openA-4	17.44	0.22	81.23
openA-5	9.88	0.07	126.69
openA-6	10.05	0.07	122.50
openA-7	8.81	0.06	159.31
openA-8	8.21	0.05	183.37
openA-9	9.27	0.06	143.92
openA-10	8.48	0.05	171.82
openA-11	8.49	0.05	171.40
openA-12	10.06	0.07	122.22
openA-13	10.60	0.08	110.02
openA-14	10.44	0.08	113.45
openA-15	10.16	0.08	119.71
openA-16	11.35	0.09	96.01
openA-17	11.89	0.10	87.39
openB-1	30.66	0.68	17.53
openB-2	26.68	0.52	11.57
openB-3	36.95	0.99	24.35
openB-4	40.12	1.17	25.56
openB-5	31.15	0.71	26.31
openB-6	26.77	0.52	22.99
openB-7	27.41	0.55	21.93
openB-8	25.08	0.46	26.21
openB-9	28.95	0.61	19.66
openB-10	28.87	0.61	19.77
openB-11	25.93	0.49	24.52
openB-12	29.15	0.62	19.40
openB-13	28.41	0.59	20.42

Table E.2 Bubble size and surface area generation rate data for tests performed in packed laboratory-scale column.

test #	Ubt (cm/s)	db (cm)	Sb (s^{-1})
packA-1	17.46	0.22	54.06
packA-2	16.21	0.19	78.40
packA-3	11.94	0.10	57.75
packA-4	16.22	0.19	15.67
packB-1	24.72	0.44	26.98
packB-2	32.93	0.79	30.40
packB-3	22.58	0.37	16.16
packB-4	29.52	0.63	28.37
packB-5	38.53	1.08	27.76
packB-6	27.60	0.55	32.46
packB-7	28.85	0.61	29.70
packB-8	29.10	0.62	29.19
packB-9	28.28	0.58	30.91
packB-10	28.92	0.61	29.55
packNO-1	27.87	0.57	21.22
packNO-2	34.70	0.88	27.37
packNO-3	31.79	0.74	24.46
packNO-4	38.17	1.06	28.28
packNO-5	36.31	0.96	25.00
packNO-6	35.64	0.92	25.95
packNO-7	35.75	0.93	25.79
packNO-8	36.11	0.95	25.27
packNO-9	35.29	0.91	26.47

Table E.3 Bubble size and surface area generation rate data for tests performed in pilot-scale column.

test #	Ubt (cm/s)	db (cm)	Sb (s^{-1})
open50-1	33.80	0.83	21.21
open50-2	32.91	0.79	21.99
open50-3	33.80	0.83	21.63
open50-4	33.73	0.83	21.72
open50-5	31.96	0.74	23.39
open50-6	34.97	0.89	19.47
open50-7	32.03	0.75	23.45
open50-8	30.75	0.69	25.28
open50-9	30.75	0.69	24.93
pack50-1	34.45	0.86	19.30
pack50-2	36.86	0.99	16.68
pack50-3	34.46	0.86	19.22
pack50-4	32.77	0.78	20.95
pack50-5	30.04	0.66	24.93
pack50-6	29.03	0.61	26.79
pack50-7	30.43	0.67	24.21
pack50-8	29.90	0.65	25.71
pack50-9	28.66	0.60	27.99
pack50-10	27.93	0.57	28.94
pack50-11	30.05	0.66	26.55
pack50-12	30.07	0.66	25.88
pack50-13	29.87	0.65	28.26
pack50-14	31.24	0.71	26.00
pack50-15	32.59	0.77	24.59
pack50-16	32.30	0.76	24.56

Appendix F

Table F.1 Summary of pilot column scale up.

	column cell				
	open	packed		packed (no sparger)	
model *	P.F.D.	P.F.	P.F.D.	P.F.	P.F.D.
τ exp (min)	12.29	13.36	13.36	11.75	11.75
k_c (min-1)	0.21	0.28	0.28	0.28	0.28
dc (m)	0.5	0.5	0.5	0.5	0.5
Hc (m)	3.35	3.41	3.41	3.39	3.39
ε_g	0.11	0.11	0.11	0.13	0.13
J_g (cm/s)	2.92	2.75	2.75	3.11	3.11
J_a (cm/s)	0.40	0.38	0.38	0.42	0.42
Q_a (cm/s)	47.63	44.59	44.60	49.07	49.33
Nd	2.48	0	2.55	0	2.35
a	5.11	1	6.22	1	5.67
Rf	0.75	0.75	0.75	0.75	0.75
Rc	0.6493	0.8481	0.7131	0.8382	0.6980
Rfc theo	0.5814	0.8072	0.6508	0.7953	0.6341
Rfc exp	0.6351	0.7091	0.7091	0.6194	0.6194

* model refers to the scale up model (P.F.D. = plug flow dispersion and P.F. = plug flow)

Table F.2 Summary of industrial columns. Feed flow to one bank of cells = 15000 l/min; feed throughput = 282 tonnes/day (1.3% consistency).

	column type						
	open			packed			
sparger	A	A	B	A	A	B	none
= columns	1	2	4	1	2	3	3
dc (m)	2.65	1.78	3.18	2.70	1.80	2.82	2.83
Hc (m)	12	12	16	12	12	16	16
τ (min)	3.18	2.87	24.53	3.29	2.93	15.74	15.81
kc (min-1)	0.97	0.97	0.21	0.97	0.97	0.28	0.28
ε_g	0.25	0.25	0.1	0.25	0.25	0.1	0.1
Qf (l/min)	15000	7500	3750	15000	7500	5000	5000
Qw (l/min)	663	298	951	686	305	749	753
Qa (l/min)	15630	7783	4654	15652	7789	5712	5715
J_g (cm/s)	1.5	1.5	3	2	2	3	4
J_f (cm/s)	4.52	5.04	0.79	4.37	4.92	1.33	1.33
J_w (cm/s)	0.2	0.2	0.2	0.2	0.2	0.2	0.2
J_a (cm/s)	4.71	5.23	0.98	4.56	5.11	1.52	1.52
Rf	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Rfc	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Rc req	0.8889	0.8889	0.8889	0.8889	0.8889	0.8889	0.8889
Nd	0.23	0.14	1.44	0.26	0.16	0.82	0.90
a	1.96	1.59	5.49	2.08	1.66	3.91	4.13
Rc cal	0.8889	0.8889	0.8889	0.8889	0.8889	0.8889	0.8889

Table F.3 Determination of rate constant in open laboratory column using sparger A.

test #	flow (ml/s)		density (g/ml)		consistency (%)		ERIC (ppm)		τ (min)	eff (%)	Rc(%)	kc (min^{-1})
	feed	accepts	feed	accepts	feed	accepts	feed	accepts				
openA-5	52.1	66.1	1.003	1.002	1.24	0.89	763.84	124.00	6.41	83.77	85.23	0.61
openA-6	107.5	116.6	1.003	1.002	1.28	1.14	815.96	148.61	3.04	81.79	82.42	0.97
openA-7	61.3	69.8	1.003	1.002	1.23	1.03	765.38	148.16	5.42	80.64	81.56	0.51
openA-8	33.8	39.1	1.003	1.002	1.28	0.84	835.21	146.82	10.01	82.42	86.67	0.56
openA-9	78.1	87.3	1.003	1.002	1.32	1.13	747.27	151.78	4.19	79.69	80.58	0.62
openA-10	47.0	53.7	1.003	1.002	1.26	0.97	668.81	138.54	7.19	79.29	81.80	0.39

Table F.4 Determination of rate constant in open laboratory column using sparger B.

test #	flow (ml/s)		density (g/ml)		consistency (%)		ERIC (ppm)		τ (min)	eff (%)	Rc(%)	kc (min^{-1})
	feed	accepts	feed	accepts	feed	accepts	feed	accepts				
openB-7	61.30	79.50	1.003	1.002	1.16	0.87	767.11	301.76	5.42	60.66	61.78	0.23
openB-8	29.10	47.30	1.003	1.002	1.14	0.68	833.62	236.25	8.98	71.66	72.55	0.20
openB-9	104.70	122.30	1.003	1.003	1.21	0.97	853.30	408.18	3.47	52.16	55.21	0.29
openB-10	54.30	71.70	1.003	1.002	1.15	0.80	835.36	311.06	6.04	62.76	65.83	0.23
openB-11	21.40	38.80	1.003	1.002	1.21	0.64	849.00	285.86	11.73	66.33	67.74	0.13
openB-12	73.30	90.80	1.003	1.003	1.20	0.96	864.99	428.86	4.76	50.42	50.87	0.18
openB-13	36.50	54.00	1.003	1.002	1.25	0.78	836.31	311.31	7.97	62.78	65.67	0.18

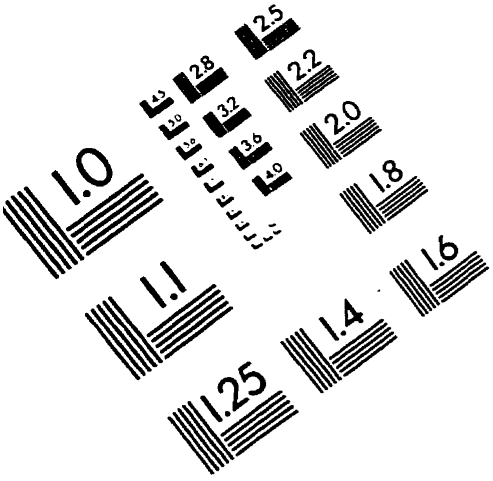
Table F.5 Determination of rate constant in packed laboratory column using sparger B.

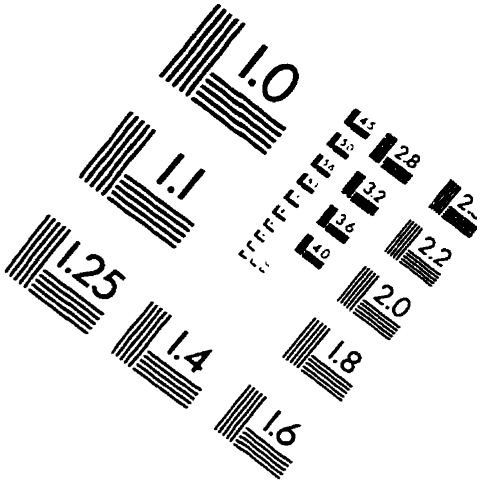
test #	flow (ml/s)		density (g/ml)		consistency (%)		ERIC (ppm)		τ (min)	eff (%)	Rc(%)	kc (min^{-1})
	feed	accepts	feed	accepts	feed	accepts	feed	accepts				
packB-6	65.70	80.20	1.003	1.002	1.28	0.87	819.21	254.95	5.00	68.88	74.20	0.38
packB-7	33.80	44.90	1.003	1.002	1.34	0.92	810.35	228.19	9.08	71.84	74.34	0.21
packB-8	105.80	120.80	1.003	1.002	1.20	1.05	761.30	265.23	3.40	65.16	65.23	0.41
packB-9	24.40	33.90	1.003	1.002	1.30	0.88	749.59	182.28	11.74	75.68	77.15	0.19
packB-10	41.70	54.90	1.003	1.002	1.29	0.93	863.24	316.72	7.32	63.31	65.21	0.19

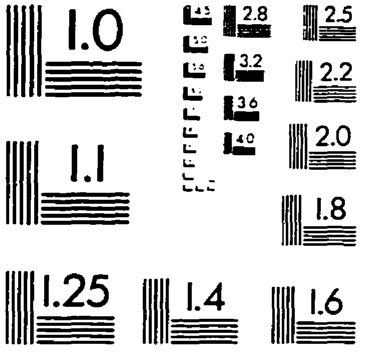
Table F.6 Determination of rate constant in packed laboratory column using no sparger.

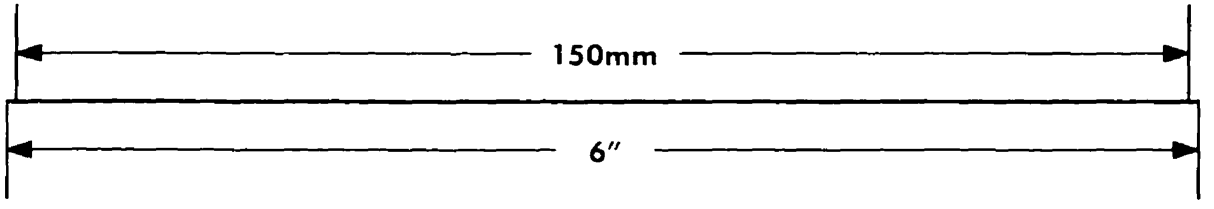
test #	flow (ml/s)		density (g/ml)		consistency (%)		ERIC (ppm)		τ (min)	eff (%)	Rc(%)	kc (min^{-1})
	feed	accepts	feed	accepts	feed	accepts	feed	accepts				
packNO-5	59.60	74.20	1.003	1.002	1.36	1.04	855.65	302.52	5.31	64.64	66.37	0.27
packNO-6	34.40	46.90	1.003	1.002	1.33	0.93	882.92	230.75	8.37	73.87	75.11	0.24
packNO-7	98.10	112.70	1.003	1.002	1.38	1.08	904.69	347.06	3.48	61.64	65.54	0.40
packNO-8	41.90	55.00	1.003	1.002	1.33	0.92	851.32	232.28	7.12	72.72	75.25	0.28
packNO-9	20.40	32.40	1.003	1.002	1.31	0.76	840.49	183.66	11.60	78.15	79.89	0.22

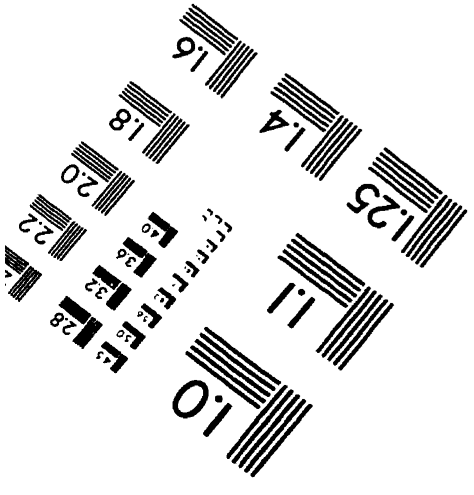
IMAGE EVALUATION
TEST TARGET (QA-3)

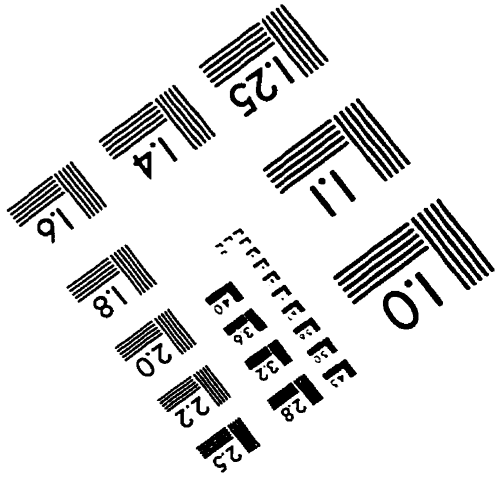












APPLIED IMAGE, Inc
1653 East Main Street
Rochester, NY 14609 USA
Phone: 716/482-0300
Fax: 716/288-5989