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In-Plant Comparison of Internal and External Spargers for Flotation Column Deinking

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A thesis submitted to the Faculty of Graduate Studies and Research
in partial fulfillment of the requirements of the degree of
Master of Engineering

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Anderson's Law:

"I have yet to see any problem, however complicated, that, when looked at in the right way, did not become still more complicated"

Abstract

The degree of waste paper recycling has been increasing steadily in North America over the last decade. Today, it is recognized that the flotation deinking process is one of the most important processes in waste paper recycling. This is demonstrated by the numerous variety of industrial flotation cell technologies currently available. Column flotation, developed in the mineral processing industry, is proposed as an alternative to other flotation technologies due to its low capital costs and improved separation performance. The flotation column requires an air sparging device to produce bubbles. Previous experimentation has shown that columns run with internal porous spargers initially produced excellent ink recoveries and low organic losses but eventually the sparging system plugged and performance deteriorated.

In this work, an air sparging technique, based on a static inline pipe mixer was compared to a porous sparger. Both air sparging systems were evaluated in-plant on a lab scale flotation column to determine their relative merits, confirm previous work and compare to a circuit of full scale deinking cells. The effects of gas rate, retention time, wash water rate, froth height were investigated. It was found that the static mixer sparger was an excellent alternative to conventional porous spargers due to its stable operation and ability to control bubble size. As with porous spargers, the bubble surface area rate produced by the sparging system was found to be an important parameter in determining ink recovery. Two flotation circuits based on columns with the two competing sparging systems were scaled up using long term test data and compared. Operational boundaries for the static mixer sparger system were also defined.

Résumé

L'étendue du recyclage du papier n'a que progressé en Amérique du Nord depuis la dernière décennie. De nos jours, il est reconnu que le procédé de désencrage par flottation est un des procédés les plus importants dans le recyclage du papier. Ceci est démontré par les nombreuses variétés de technologies industrielles de cellules de flottation disponibles actuellement. La flottation en colonne, développée dans l'industrie de traitement des minerais, est proposée comme alternative à d'autres technologies de flottation à cause de ses coûts capitaux bas et de l'amélioration de la performance de séparation. La flottation en colonne requiert un barboteur. Des expériences antérieures ont démontré que les colonnes fonctionnant avec des barboteurs à pores internes produisaient initiallement d'excellentes récupérations d'encre et des pertes organiques basses, mais qu'éventuellement le système du barboteur s'obstruait et la performance se détériorait.

Dans cette étude, une technique de barboteur, basée sur un mélangeur de conduit interne statique a été comparé à un barboteur poreux. Les deux systèmes de barboteurs ont été évalués en usine, à l'échelle de laboratoire, sur une colonne de flottation afin de déterminer leurs mérites relatifs, confirmer le travail antérieur et comparer à un circuit grande échelle de cellules de désencrage. Les effets du taux de gaz, du temps de retention, du taux d'eau de lessivage, et de la hauteur de l'écume ont été étudiés. Il a été déterminé que le barboteur à mélangeur statique est une excellente alternative aux barboteurs poreux conventionnels à cause de son opération stable et de la capacité de contrôle de la grosseur de bulle. Tout comme avec les barboteurs poreux, le taux de surface des bulles produit par le système de barboteur a été déterminé être un paramètre important dans la détermination de la récupération d'encre. Deux circuits de flottation basés sur des colonnes avec les deux systèmes de barboteurs en compétition ont été portés à grande échelle en utilisant des données à long terme et comparés. Les limites opérationnelles du système de barboteur à mélangeur statique ont aussi été définies.

Acknowledgments

I would like to thank the following people and organizations for their contributions to my work and experiences at McGill University:

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◘ CHAPTER ONE ◘

Introduction

1.1 OVERVIEW

For more than 200 years the search has been going on for ways of removing printing ink to produce an acceptable white paper from printed waste paper. It was only about 30 years ago, however, that a breakthrough was made in large-scale deinking of waste paper using the froth flotation principle. The first flotation deinking cells and plant technology were designed on the basis of equipment used in the mineral processing industry (Schulze, 1991). Today, it is recognised that the flotation process is one of the most important sub-processes in a waste paper recycling mill, as it provides an effective means of removing ink particles from recycled pulp (Dessureault et al., 1995).

Recently, the pulp and paper industry has once again transferred technology from the mineral industry in the form of the flotation column. The flotation column, sometimes referred to as the Canadian Column, was patented in the early 1960s by Boutin and Tremblay (Boutin, 1964) for the extraction of bitumen and oil from the Athabasca tar sands. It was only in 1983 that the technology was commercialized with the first flotation column installation at Les Mines Gaspe for molybdenum cleaning. Since mid-1980s many variations in the design of the flotation column have been evaluated and extensive work was done leading to numerous improvements and applications. Properly designed columns offer advantages in terms of reduced floor space, reduced operating and capital costs, and simplified circuits (Luttrell et al., 1994). Other new applications for flotation columns are found in soil decontamination, food processing, and de-oiling. It is unfortunate, however, that some of the advantages of columns are not fully obtained in practice. These shortcomings are frequently due to deficiencies associated with the design, scale-up and operation of the bubble generating system. Figure 1.1 shows an industrial sized flotation column.

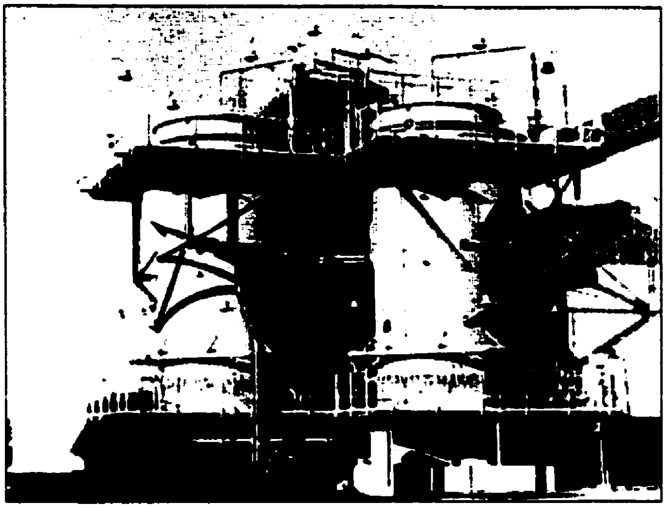


Figure 1.1 Mineral flotation columns with sparging system located near the bottom.

An effective air sparging system must be capable of producing small, uniformly sized bubbles at a desired aeration rate (Huls et al., 1991). Small bubbles can improve kinetics by enhancing the capture efficiency of fine particles (Yoon and Miller, 1982, Dobby and Finch, 1986). In addition, smaller bubbles may increase the gas carrying capacity by increasing the bubble surface area rate (Finch and Dobby, 1990). Many different generating systems are now available for column flotation cells (Al Taweel, 1989; Dobby and Finch, 1991; Rubinstein, 1995), the most common methods for generating air bubbles can be broadly divided into two types: internal and external spargers.

The most common spargers are the internal bubble generators fabricated from filter cloth or perforated rubber. The major disadvantage of these spargers is that they generate relatively large bubbles, often as large as 2-3 mm in diameter (Brake et al., 1996). Porous metal and permeable ceramic tubes can also be used to produce small air bubbles, but they are prone to plugging and must be frequently cleaned. External bubble generation is that where gas and liquid (or slurry) are brought into contact external to the column. Examples of these devices include the United States Bureau of Mines (USBM)/Cominco sparger, Minnovex and Cominco variable gap spargers, and the Microcel sparger.

In the USBM/Cominco sparger, air and water (both at high pressure) are contacted in a chamber containing a bed of ground quartz or ceramic spheres. The discharge from the chamber is carried through steel pipes to the column were it is then expelled through holes about 1 mm in diameter located along air lances placed near the bottom of the column. The Cominco sparger is similar to the USBM sparger except that the pressurized air and water are contacted in a "T" section before being delivered through the air lances. The lances have 1 mm holes with tungsten-carbide inserts to minimize wear. In the Minnovex variable gap and Cominco Sparjet spargers, high pressure air (without water) is passed through an annular gap to generate bubbles. The gap is adjustable to account for wear. In the Microcel column sparger, shear is used to form bubbles by forcing slurry and air over the blades of an in-line static mixer. The advantages of these techniques compared with internal systems include less chance of plugging with solids or precipitates, on-line sparger maintenance, and some control over bubble size (Cienski et al., 1990). The main disadvantage being in extra water entering the column (USBM and Cominco design), wear problems and the more complicated operation.

To date excellent results (high ink removal and low fiber loss) have been achieved using internal spargers in the deinking of various waste paper furnishes (Petri, 1994; Watson et al., 1996; Dessureault et al., 1995; Carabin et al., 1997; Leichtle, 1998). However, over the long term it has been found that that the performance of both laboratory and full-scale flotation columns have diminished due to plugging of the air sparging system. To realize the column's advantage in the de-inking of recycled paper, a reliable method of bubble generation is required.

This thesis will compare the performance of a column using a porous stainless steel sparger with an external sparging system. The external system is based on a static inline mixer such as used in the Microcel flotation column. The expected benefits of this flotation system are increased ink removal efficiency, low fiber loss, increased particle collection rates, increased unit column capacity, and reduced height in comparison to the conventional column (Brake et al., 1996). Wear problems are not anticipated due to the non-abrasive nature of paper fiber slurries. The disadvantage of this sparger technology is the requirement of a pumping system to achieve high liquid velocities through the mixer.

1.2 THESIS OUTLINE

Because the system under consideration is a real industrial separation, there is always the possibility of overlooking relevant items. At the risk of including a large amount of background information the author feels that what has been provided is a basic overview of waste paper recycling and deinking. Numerous references have been included to enable the reader to explore certain areas in greater depth.

Chapter 1 introduces the topic under study by briefly describing the recent application of the flotation column to waste paper deinking. An outline of the project is contained at the end.

The scope and purpose of this undertaking is discussed in Chapter 2.

Fundamentals with reference to waste paper recycling and flotation deinking are briefly considered in Chapter 3 to outline the basic knowledge required for understanding the separation process as a whole. First the state of waste paper recycling in today's society is discussed, followed by a review of waste paper contaminants and removal steps in a typical recycling mill. This is followed by a brief review of factors important to flotation deinking. To close, modern flotation deinking cells are discussed.

Chapter 4 describes the basic principles and nomenclature used in column flotation and describes the two spargers (internal and external) examined in this thesis. This is followed by a description of the various methods and techniques used to quantify column deinking performance. Finally, to augment Chapter 3, flotation factors which directly influence column flotation are discussed.

Chapter 5 comprises the experimental program and gives details about the equipment and its specific configuration. The experimental program is outlined. Details on characteristics of the flotation are presented.

Test results and their subsequent discussion are presented in Chapter 6. A detailed comparison between the two air sparging systems in terms of performance, operational stability and cost is made. Two full scale column installations based on Bowater's flotation plant throughput are also described.

Chapter 7 states the conclusions and proposes some recommendations for future efforts in this area.

All reference material is in Chapter 8 while all experimental data is located in the appendices at the end of this thesis.

✣ CHAPTER TWO ✣

Scope and Significance

The primary focus of this study was to compare the performance of two air sparging systems (porous and static mixer spargers) on a laboratory column flotation in a deinking application. The main question being asked is whether column flotation deinking using porous internal spargers can be replaced or improved by an external sparging system and still maintain the performance as indicated by previous studies. Bowater's (formerly Avenor) waste paper recycling mill in Gatineau, Quebec was the site of the test work because fairly large quantities of flotation ready paper pulp were required. Since the site included an industrial flotation circuit, comparisons with existing deinking technology could also be made.

The evaluation was based on operational observations (ink recovery, fiber recovery, and operational stability) and the economics of a proposed full scale installation to replace Bowater's existing flotation circuit. A range of operating conditions were considered in each case, but no changes to mill pulp chemistry were made. For the internally sparged column (porous sparger), the effect of air rate, retention time, froth depth, wash water rate and column height were investigated. The externally sparged column (static mixer sparger) was investigated with regards to air rate, retention time, static mixer velocity and column height. To determine the size and cost of these two types of flotation columns for the proposed installation, two companies specializing in column flotation systems were contacted.

In the end, it is hoped that this project will lead into new areas of research: application of columns for novel separations, development of new sparging systems and possible full scale installations of deinking flotation columns in North America, to name some.

✻ CHAPTER THREE ✻
Background

3.1 WASTE PAPER RECYCLING

Waste paper is increasingly regarded as alternatively a valuable resource or a nuisance by the global pulp and papermaking industry, government, environmental groups and other interested parties. Several things are abundantly clear, however; waste paper collection and re-use are increasing rapidly around the world and that the entire paper recycling issue is one of the most important for the industry in the 1990s. Other issues facing the pulp and paper industry include paper demand variations, chemical emissions, effluent controls, industry restructuring, and consolidation (Payne, 1992).

3.1.1 Current Canadian Trends

In the late '80s, the use of recovered paper in the production of Canadian paper and board started to accelerate (Figure 3.1). By investing over 1.5 billion dollars since 1990 in recycling equipment, Canadian paper and board producers have made recovered paper an integral part of their business.

Recycled fibers derived from waste papers of various types account for approximately 25 percent of the total fibrous material used by Canadian paper and board mills (CPPA, 1998). In 1997, the Canadian pulp and paper industry transformed 4.7 million tonnes of old newspapers, corrugated containers, boxboard, and other grades of paper into new newsprint, containerboard, boxboard, construction paper, kraft and sanitary papers. To meet the demand for recycled products, Canada has become the worlds largest importer of wastepaper, importing approximately 2 million tonnes of recovered paper from the United States a year (CPPA, 1998). It is forecast that by the start of the next century world waste paper collection and demand could rise to around 140 million tonnes from 83 million tonnes in 1990 (Payne, 1992).

3.2 PRINTING TECHNOLOGY AND INK CHEMISTRY

This review of printing technology and ink chemistry is intended to provide a background since the method used to put ink on the paper, and keep it on, has a significant impact on deinking. Several reviews have been given by: (Aspler, 1998; Smook, 1997, Doshi, 1991; and Shrinath, 1991)

3.2.1 Printing Processes

There are five major types of printing processes that may be classified into two groups as follows:

Impact Printing	Non-impact Printing
Letterpress	Laser
Lithography (Offset)	Xerographic
Gravure	
Flexography	

Each printing technology places different demands on inks. Different inks vary in composition to meet these demands. Ink particle size, geometry and surface chemistry determines the efficiency of the subsequent deinking operations (Section 3.4.1). Ink chemistry determines ink particle size after pulping print paper (Table 3.1).

Table 3.1 Ink particle size after pulping old paper (Ferguson, 1992a)

Printing Process	Ink Particle Size (microns)	
	Uncoated Paper	Coated Paper
Letterpress	2-30	10-100
Offset	2-30	5-100
Gravure	2-30	5-30
Flexography	0.3-1	0.7-2
Laser, Xerographic	40-400	40-400

Considering these particle size ranges and the dependence of the effectiveness of different deinking operations as a function of ink particle size, it becomes clear that ink type determines how effective the deinking process will be. For instance, Figure 3.2 indicates that wash deinking will be most efficient on small flexographic particles while a combination of flotation, cleaning and fine screens will be effective in deinking large particles produced from toner inks. Since paper coatings also affect particle size, they can also affect deinking (Borchardt, 1997b).

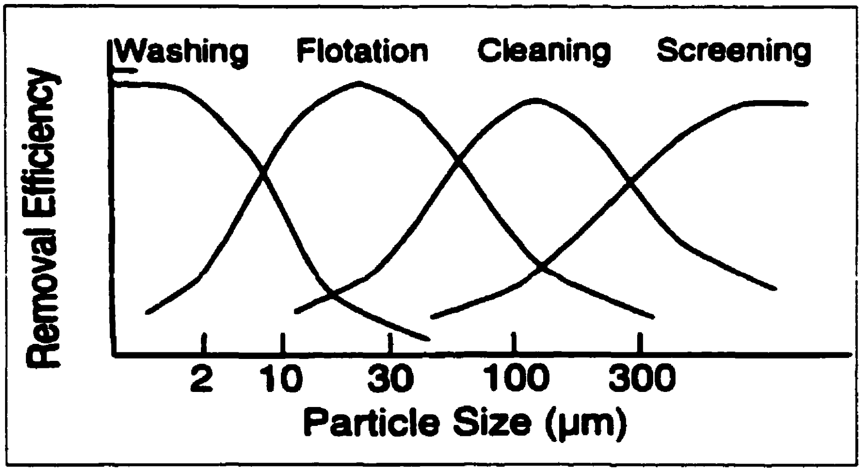


Figure 3.2 Optimum particle size ranges for the various unit deinking operations (Shrinath et al., 1991).

3.2.2 Ink Composition

At the present time there are approximately fifteen million ink formulations on file at the US National Printing Ink Research Institute with tens of thousands more being introduced each year (Aspler, 1998). Numerous reviews of ink composition have been written (Wasilewski, 1987; Bassemir, 1982; Aspler, 1994; and Ferguson 1992c). It is only a slight exaggeration to say that each paper-press combination requires different ink. The make up of the ink is determined by the type of paper on which it is applied, the method of application (printing process), the drying process, and the end use of the paper. Ink ingredients usually fall into three categories:

1) Vehicles
2) Pigments
3) Modifiers

The ink vehicle is the largest constituent of ink and is the major factor determining the ease of deinking. The vehicle helps transfer the pigment or dye to the paper and aids in binding it there. The vehicle is a fluid that provides the ink with the proper liquidity, i.e. acceptable handling properties. Vehicles are generally vegetable oils, mineral distillates, resins (natural and synthetic), plastics, and volatile solvents (Shrinath et al., 1991). However, it is important to remember that it does not dissolve the pigment, it disperses it. In addition to the solvent, the vehicle contains a binder. The binder binds pigment particles together and attaches them to the surface of the paper. Dried binders are usually polymer films and may be tightly crosslinked which cause difficulties for deinking operations. (Ferguson, 1992c).

Pigments are coloured materials insoluble in the ink vehicle. They are very small solid particles dispersed in the vehicle. Dyes are seldom used because they tend to soak into the paper too much (Borchardt, 1997). The pigment provides colours and opacity to the ink and is important in delivering viscosity and the desired flow characteristics. The most common pigment is carbon black on which more than 80 % on all printing inks are based.

Modifiers are added to give inks particular chemical or physical properties. Modifiers include waxes, binders, wetting agents, plastisizers, and drying agents. Modifiers are generally used at low levels and therefore do not affect ink removal.

A broad range of diverse inks are used in the various printing methods today, and new formulations are continually being developed. While these inks have good printing characteristics and are welcome news to the printing industry, they pose challenging problems to the paper industry, which is facing pressure to increase the amounts of recycled fiber in paper making furnishes. The growth of desktop publishing and the high quality print offered by laser printers can only lead to an increase in the use of laser-printed inks. Deinking technology and chemistry must continue to evolve if industry is to keep pace with these developments.

3.3 WASTEPAPER RECYCLING SYSTEMS AND CONTAMINANTS

In earlier times, recycling systems were relatively simple in design due to a number of factors (Spangenberg, 1993). The raw material (wastepaper) was abundant and easy to obtain because of the small number of mills using recycled fiber. Contaminants were less varied in type and composition. Systems for processing recycled fiber were open rather than closed loops. Fresh water was readily available, and plant wastes could be flushed directly into rivers and lakes. Bleaching chemicals were chosen based on efficiency and cost rather than their effect on the environment. The process of recycling fiber today has become more complex (Carr, 1991). A flow sheet for a typical modern deinking mill flow is shown in Figure 3.3.

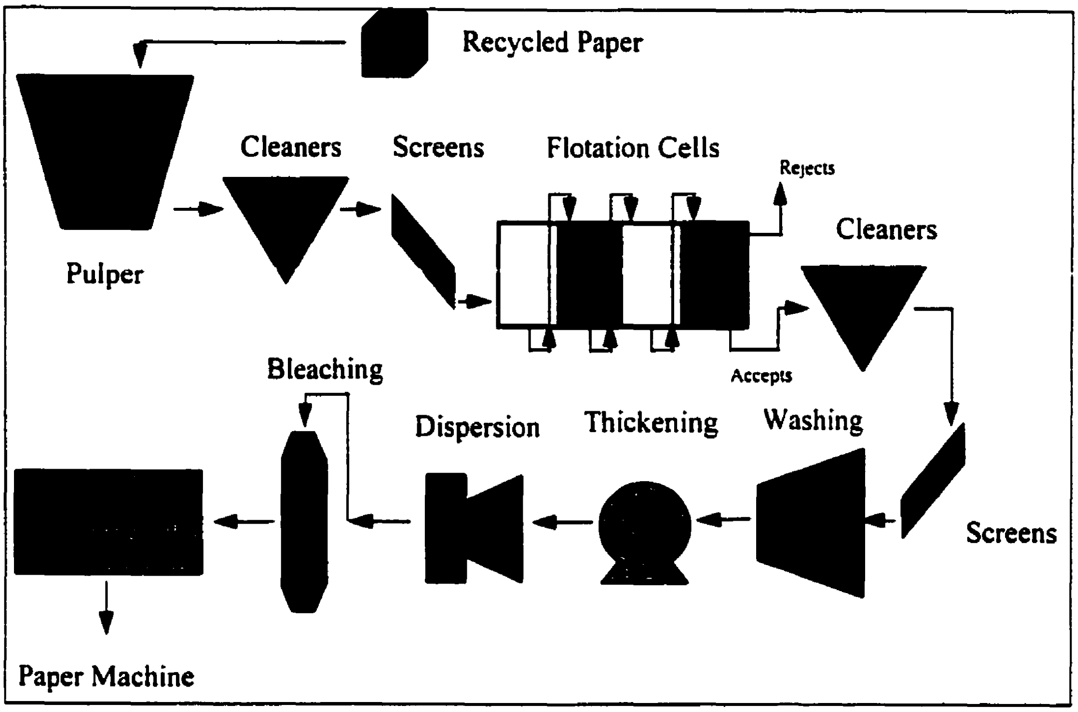


Figure 3.3 Typical deinking mill flow sheet

Systems must now be engineered and operated in a closed loop with facilities for treating solid wastes. These systems often run at less than optimum conditions as contaminants separated from fiber streams are later re-mixed into accepts (cleaned pulp) with the idea of increasing fiber recovery or saving water. Systems for processing recycled fibers can be configured in various arrangements. Determining factors include the final paper quality desired and the type and amount of contaminants in the recovered paper supplies.

The best way to eliminate contaminants from the finished paper is not to allow them into the recycling mill's warehouse. In its own best interests, a recycled fiber mill must be aware of the amount and nature of the contaminant in incoming bales of recovered paper. 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" and are found in book bindings, label backings and adhesive coatings (Smook, 1997). Table 3.2 summarizes some common contaminants and their sources. It is generally accepted that contaminants should be removed from the pulp stream as early in the system as possible and at as large a size as practical. The first sorting is a manual screening of raw materials; this may take place at the mill or at a separate receiving center. If the bales of waste paper meet the quality demands of the mill, they are then ready to proceed to the deinking process.

Table 3.2 Common contaminants and their sources (Merriman, 1993)

Contaminant	Typical Sources	Particle Size	Specific Gravity
Hot Melts	Adhesives and coatings	40 μm- 4000 μm	0.95 - 1.1
Polystyrene Foam	Blocks and beads used in packaging	400μm +	0.3 - 0.5
Dense Plastic Chips	Blister packs and see-through products	400μm to larger than 4000 μm	1.04 - 1.1
Latex / Rubber	Adhesives and coatings, rubber bands	40μm to 4000 μm	0.9 - 1.1
Pressure Sensitives	Roll splices and case seals	40μm to 400 μm	0.9 - 1.1
Waxes	coatings and laminates	partially dissolved less than 40 μm	0.9 - 1.0
Wire / Metals	bail wire and paper clips	larger than 4000 μm	6 - 9
Fillers and Coatings	ash and varnishes	less than 40 μm	1.8 - 2.6
Asphalt	roads	less than 40μm to 400 μm	1.1 - 1.5
Ink	newspaper and magazines	partially dissolved to 400 μm	1.2 - 1.6
Sand	bale storage, blue boxes	40 μm +	2.2 - 2.6

3.4 A MODERN DEINKING FACILITY: BOWATER'S GATINEAU MILL

Bowater Pulp and Paper's (formerly Avenor) Gatineau, Québec mill is an example of modern deinking facility where newsprint, containing recycled fibers, is produced. The makeup of the newsprint produced consists of 59 % thermomechanical pulp (TMP), 40 % recycled pulp and 1 % kraft pulp. The deinking plant, which was built in 1992 for the cost of approximately 100 million dollars (Stevenson, 1992), recycles 500 tonnes per day of old newspapers (ONP) (70 %) and old magazines (OMG) (30 %).

3.4.1 Deinking Process Equipment

The main stages in the deinking plant include: high-consistency pulping, coarse cleaning, flotation, fine cleaning, thickening, disperging, and bleaching (Stevenson, 1992).

3.4.1.1 Pulping Stage

The pulping process begins with the conveyor system that feeds a newspaper and magazine mixture to the pulper. Pulping in a deinking plant is usually done on a batch basis, although continuous pulping is used for some applications (Crow and Secor, 1987). Continuous pulping is possible when the quality of the recycled paper is uniform and the chemistry can be kept simple. The function of the pulper is to de-fiber the paper and to detach the ink particles from the fiber, while keeping the undesirable materials large enough to be removed by downstream processes. The pulper is often described as the heart of the deinking process and is equivalent to liberation for mineral processing. Most batch pulpers are circular tubs equipped with a helical bottom rotor and baffles to interrupt the pulp flow. Figure 3.4 shows a high consistency (high percent solids) pulper.

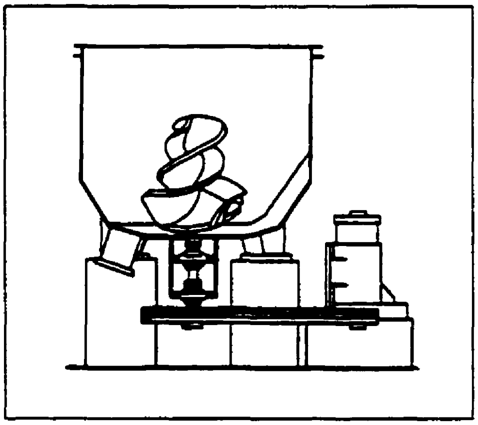


Figure 3.4 High consistency pulper (modified from Smook, 1997).

High consistency pulping is preferred over low consistency pulping due to faster separation of ink from fibers and less energy consumption. At this stage, the ONP and OMG are fed automatically to two high-consistency pulpers (Voith model 50) until a batch of 8 tonnes is reached. Pulping is done for approximately 30 minutes at a pH of 9.5-11, temperatures 55-70°C, and a consistency (percent solids) of 15 %. The high consistency, moderate temperature, and brisk agitation make this a good location for the addition of chemicals. Chemical addition to the pulper is necessary to assist in the removal of the undesirable materials such as ink and "stickies", and make them accessible for flotation deinking. Typical chemicals added in the pulper are sodium hydroxide, fatty acid soap, hydrogen peroxide, a chelating agent and sodium silicate (Ferguson, 1992a).

3.4.1.2 Coarse Cleaning Stage

In the coarse cleaning stage the slurry from the pulpers is diluted and 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 in the process. Secondary screening consists of high-density forward cleaners (will be described later in this chapter) which remove staples, paper clips, stones, and other "heavies" that could damage or plug the fine screens or other downstream equipment.

Pressure screens (FiberPrep SPMs) with holes 1.5 to 2 mm in diameter are then used to remove large ink particles, plastic, and pieces of glue. These screens are high technology, precision-manufactured components usually constructed from stainless steel. The pressure screen normally consists of a cylindrical screen plate and a rotor containing elements that cause pulsations near the plate surface as the rotor turns. These pulsations back flush the screen plate as often as 50 times per second to prevent fibers or contaminants from blinding the surface (Merriman, 1993). Between pulses, pressure from the pump feeding the screen forces water and useable fibers through the openings in the screen plate.

3.4.1.3 Flotation Stage

In the flotation process, the chemicals which were introduced in the pulper cause the ink particles to flocculate and produce a foam. In a deinking flotation cell the pulp is aerated at low consistencies (0.9 - 1.5 % solids). Deinking is a reverse flotation process where the ink and stickies become attached to the air bubbles, causing them to rise to the top of the cell and be removed as *rejects* while the clean fibers stay in the pulp and are removed as *accepts*. The flotation process at Bowater consists of two banks of Voith Sulzer Multi-Injector Elliptical cells (6 primary cells and two secondary cells). Figure 3.5 shows a picture of Bowater's flotation circuit.

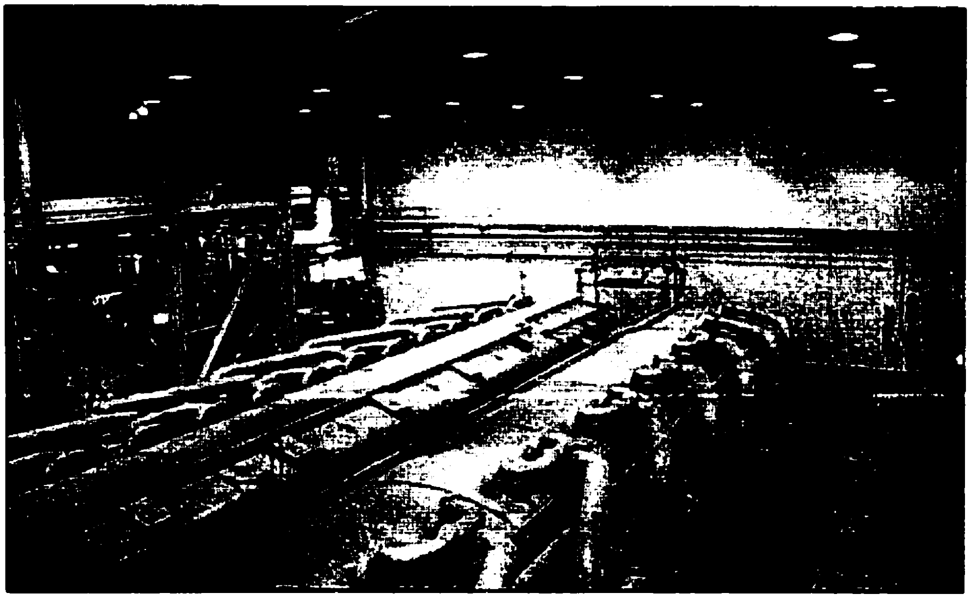


Figure 3.5 Deinking flotation cells (photo: C. Hardie).

These cells are similar in principle to the Jameson cell used in mineral processing and feature quadruple downcomers inside each tank where air is aspirated through an air inlet (Jameson and Manlapig, 1991). To minimize fiber losses and maximize ink removal, the rejects from the six primary cells are fed to two secondary cells (cleaners). The final rejects are sent for disposal and accepts from the secondary cells are returned to the primary cell. A brightness gain (defined in the Chapter 4) of 10 to 13 points across the flotation bank is typically achieved. A more detailed discussion on flotation deinking and various flotation deinking devices will be presented in Sections 3.5 and 3.6.

3.4.1.4 Fine Cleaning Stage

Fine cleaning is a three-step operation designed to maximize the cleaning efficiency at low pulp consistencies. These steps take advantage of centrifugal devices similar to hydrocyclones. They separate contaminants from the valuable fibers by centrifugal action. The first step consists of three parallel rotary cleaners which are designed to separate the lighter contaminants (S.G. less than 1.0) such as stickies, plastics and light ink compounds according to density. Figure 3.6 shows a rotary-cleaning device. These devices are rotating centrifuges which exert up to 700 Gs of centrifugal force (Stevenson, 1992). The stock at 0.5 to 2.5 % consistency is fed tangentially into the drum section which rotates at high speed and imparts a high centrifugal force to the fluid.

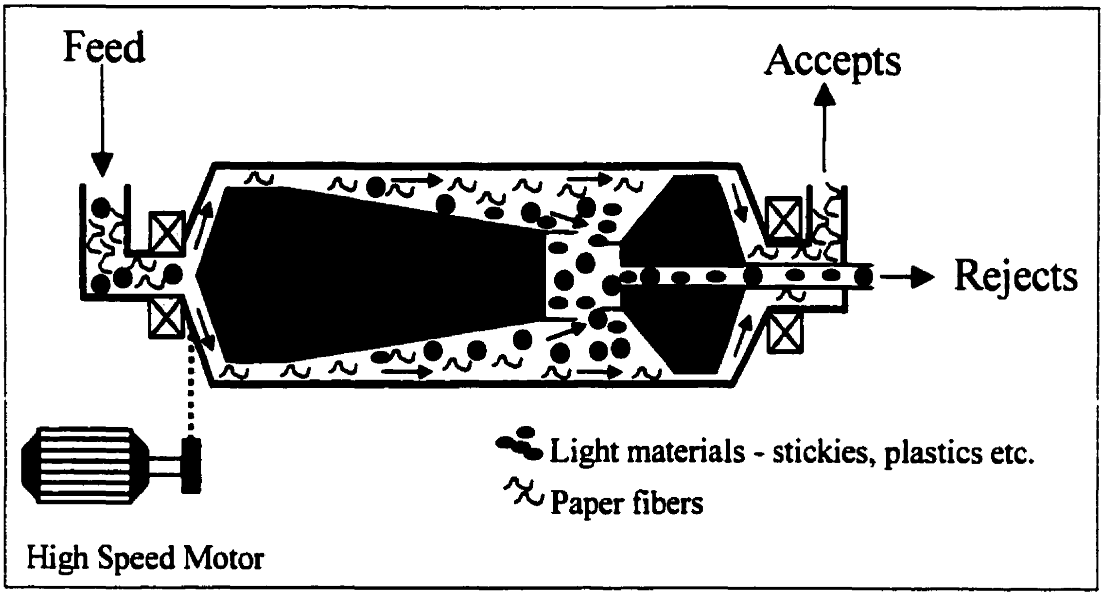


Figure 3.6 Rotary lightweight cleaner (Modified from Merriman, 1993).

Heavy particles (i.e. fibers) migrate to the drum wall, and the light contaminants (rejects) move toward the center of the drum. High centrifugal force and relatively long retention time (about seven seconds) give the centrifuge higher efficiency than reverse cleaners.

The second step treats the accepts from the rotary cleaners with five cascading stages of forward cleaners to remove ink, sand, coatings and other contaminants more dense than fiber. These cleaners are hydrocyclones in which centrifugal action is achieved by introducing the feed tangentially into the cleaner body. In a cascading system, the rejects (heavy material) from one stage are diluted and fed to the next stage. Accepts, the lightweight fraction, are then piped to the feed of the preceding stage. The cascade system design offers a compromise between reduced fiber loss, high system efficiency, and low capital and operating costs. The number of stages required for a given system will depend on production rate, required pulp cleanliness, and allowable fiber loss (Merriman, 1993). Finally, during the third step, the accepts are passed through three stages of 0.2 millimeter fine screens. Figure 3.7 shows a five stage cascading system similar to the one used at Bowater.

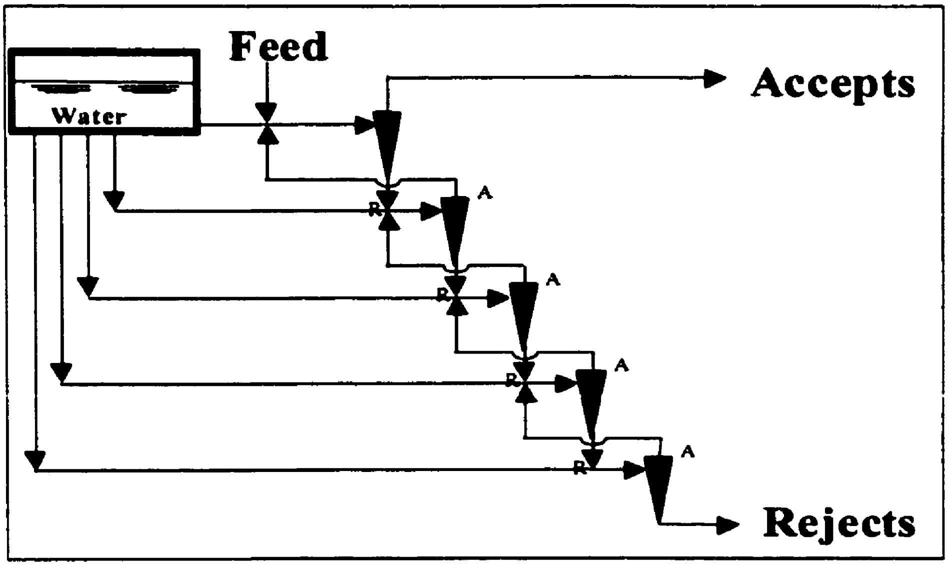


Figure 3.7 Cascading five stage forward cleaning system.

3.4.1.5 Filtering and Washing Stage

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 hot water from the paper machine and thickened to approximately 30 % consistency by two belt filter presses. 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. These presses have been well accepted by the pulp and paper industry because of their stable operation, low power requirements, low maintenance and excellent filtrate quality (Forrester, 1993).

3.4.1.6 Disperging Stage

Dispergers (Sprout Bauer Model 421) are used to refine and enhance the cleaned fibers at high temperature (85 °C to 120 °C) and high consistency (25 % - 30 %). The action of the disperger creates shear forces by mixing the stock between rotating bars and stationary bars. The dispersion of recycled fiber can be defined as the size reduction and homogeneous distribution of contaminants so as to render them invisible to the naked eye (less than 40 microns in size). Dispersion has been used successfully on inks that are difficult to remove, such as ultraviolet inks, xerographic inks, and jet-print inks (Crow and Secor, 1987). Figure 3.8 shows a typical kneader type disperger.

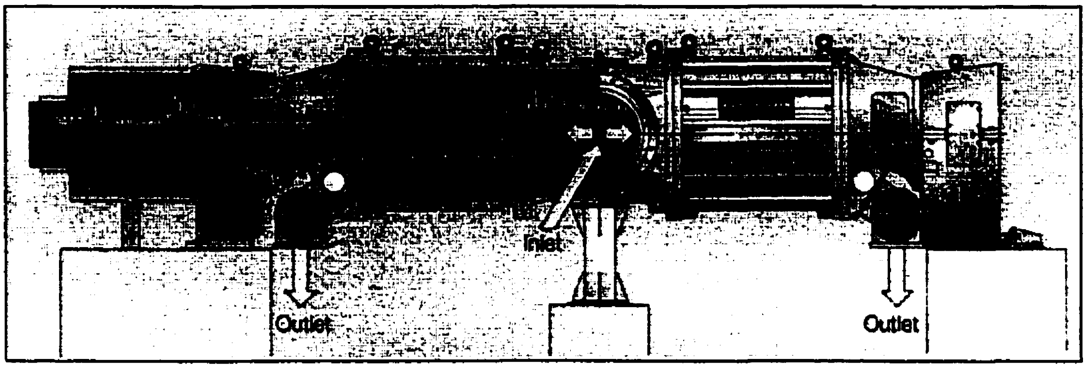


Figure 3.8 Kneader-type disperger (Reprinted by permission of Voith-Sulzer).

3.4.1.7 Bleaching Stage

Hydrogen peroxide bleaching takes place in a bleach tower. This stage is only used if the pulp is not bright enough. The stock is then diluted to about 10 % consistency with recycled water from the paper machine and is pumped to a high-density storage tank where it awaits the final step: paper making.

3.5 FLOTATION MECHANISMS

The search has been going on for ways to remove printing ink from paper for more than 200 years. It was not until about 40 years ago, however, that a breakthrough was made in large-scale deinking of wastepaper using the froth flotation principle. Froth flotation is technique that combines air bubbles and chemistry to separate ink particles from the fibers. The air is introduced in the form of bubbles at the bottom of the flotation cell. The ink particles, which are hydrophobic (either real or chemically induced) attach to the bubbles and rise to the surface of the cell where they are removed as a froth (rejects) while the clean fibers exit the bottom of the cell as accepts.

3.5.1 Flotation Theory

In flotation deinking, ink particles must attach to air bubbles rising through the pulp. For flotation to be effective, the size of the ink particles must be maintained within an optimum range of approximately 10 to 100 micrometers (Ferguson, 1992c). The printing inks typically used in magazines and newspapers are oil based and are naturally hydrophobic and difficult to disperse. The fatty acid soap added in the pulping stage probably acts as a combination flocculating / collecting agent for the ink particles.

Several models have been proposed to explain the attachment mechanism between oil-based ink particles and air bubbles under the influence of anionic surfactants such as fatty acids (Ortner, 1991, Larsson, 1987 and, Bechstein, 1975). The latest model (Putz et al., 1993) assumes that the surfactants are absorbed onto the hydrophobic surface of both the ink particles and the air bubbles. For the fatty acid based collector, the carboxylic head group of the molecule points away from the ink and bubble surfaces and are then bridged by the presence of divalent metal ions such as calcium. These calcium ions are present in magazine coatings as calcium carbonate and, if required, more is added to the flotation cells in the form of calcium chloride. Figure 3.9 represents the proposed attachment mechanism.

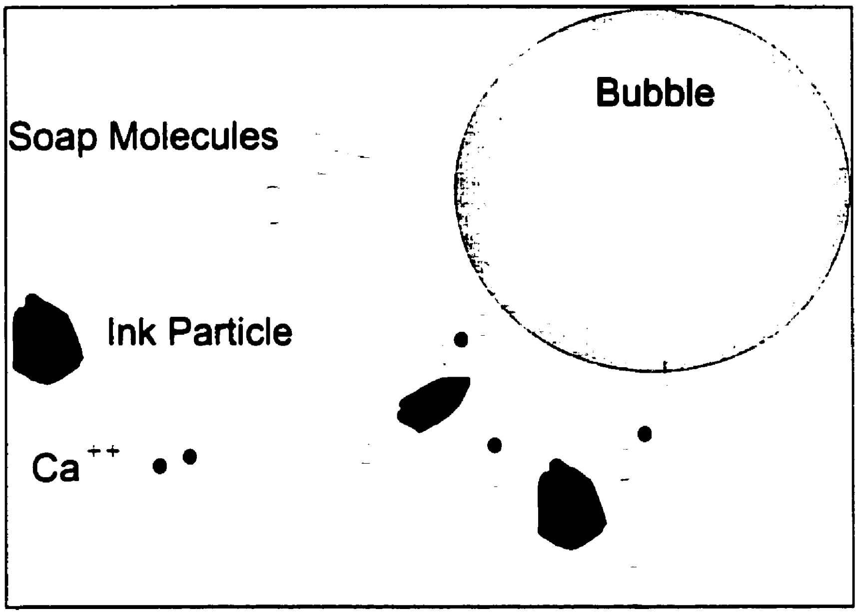


Figure 3.9 Attachment of ink particles to a bubble surface.

3.5.2 Factors Affecting Flotation Deinking

The challenge faced by the designers of flotation cells is to effectively remove the broadest range of ink particle sizes that is practically possible while keeping the fiber losses to an acceptable level. Despite the large number of flotation cell types available on the market, each cell uses the same basic principles for ink removal. Many publications detail the factors that affect flotation deinking (Linck and Britz, 1990; McCool et al., 1990, Ferguson, 1991; and Fallows, 1992). These factors can be divided into a number of categories including the effect of chemistry, particle size, bubble size and equipment type.

3.5.2.1 Role of Chemistry

A detailed discussion on pulper and flotation chemistry is not included in this thesis due to space limitations. Many papers on this subject have been published including; (Ferguson, 1992a and 1992b; Borchardt, 1997a; Woodward, 1986; Larsson et al., 1982 and Aspler, 1994). However, it is important to understand that the efficient performance of the flotation cells and the entire deinking plant is closely related to the chemistry. The choice of flotation chemicals needs to be specific to the mill, the flotation cell, water quality, wastepaper type and interactions with other chemicals in the system. Changes in pulp consistency, pH and temperature will impact flotation cell performance. The incoming stock to the flotation circuit removing ink from newspapers and magazines usually has the following characteristics: pH 8 to 11; consistency 0.7 to 1.5 %; temperature 40 to 55 °C, and water hardness 110 to 130 ppm Ca^{2+}. The pH, temperature and water hardness depend on the choice of flotation chemicals. For example, water hardness is a factor only if fatty acid soaps are used (Ferguson, 1991).

3.5.2.2 Role of Ink Particulates

It is desirable that the particles to be removed by flotation have some degree of hydrophobicity or are able to be made hydrophobic through chemical addition. In some cases the ink used in the wastepaper is not easily recoverable by flotation. Examples include flexographic ink particles as described in Section 3.2.1 which are very small (0.3 to 1 micron) and the resin surrounding the pigment particle is hydrophilic.

The type of pulper and pulping conditions in use to defiber the recovered wastepaper will affect the size and shape of particles that are delivered to the flotation circuit. Figure 3.2 (Section 3.2.1) shows the classical particle size distribution versus removal curve for a number of deinking unit operations. The key to this figure is that flotation can usually remove ink particles between 10 and 100 microns. This bell shaped curve for flotation is typical and may be arbitrarily divided into three distinct regions; fine, intermediate and coarse. The particles in each region respond in a different manner, with poor ink removal in the fine region, a "high" removal in the intermediate zone and a tailing off of ink removal in the coarse range. In the extreme ranges of the size distribution, surface forces dominate in the finer size fractions and inertia and gravity forces dominate in the coarser range. Efficient flotation is a compromise between the two extremes when floating a material with a wide size distribution.

3.5.2.3 Role of Ash Particulates

It is well known, but perhaps not as well understood, that for efficient flotation deinking of newsprint, one requires a significant amount of ash in the feed furnish. The fillers and coatings used in magazine paper can act as an inexpensive source of ash; thus, it is common practice to include magazines in flotation deinking of newsprint. Common fillers and coatings include kaolin clay, calcium carbonate and titanium dioxide. Papermakers suggest that a loading of 8-15 % ash is required in the flotation stage to optimize the removal of ink.

The true function of ash content has not been explained, although it has been shown that not enough will adversely affect the performance of the deinking system. Zabala and McCool (1988) concluded that flotation efficiency increased as clay was added. In contrast, Raimondo (1976) and Letscher and Sutman (1992) found that filler and clay, improved flotation results due to their optical properties, not by enhancing ink flotation. It has also been suggested that the filler particles contribute to ink removal by acting as an abrasive in the pulper, chipping ink flakes off the fiber (Read, 1991). In addition, clays are thought to play a role in the stabilization of the froth in the flotation cell (Letscher and Sutman, 1992). In all cases however, the addition of magazines to newspaper adds a desirable long fiber fraction for increased strength (Westenberger, 1992).

3.5.2.4 Role of Air Bubbles

In order for as many ink particles as possible to adhere to the air bubbles, the total surface area of the bubbles must be as large as possible. As shown in Figure 3.10 the specific surface area quickly increases with reducing bubble diameter, and the total number of bubbles increases even more rapidly.

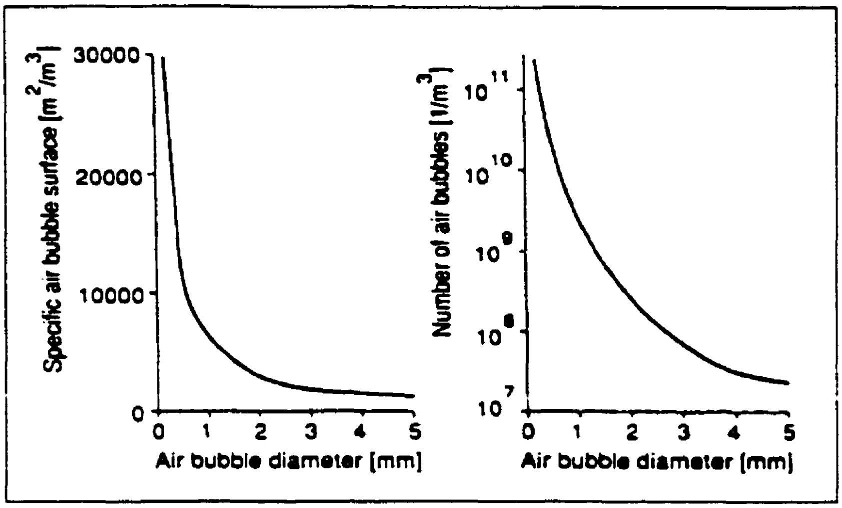


Figure 3.10 Specific bubble surface and number of bubbles as a function of bubble diameter (Linck and Britz, 1990).

It might well be concluded from this that the best effect is achieved with very small bubbles but there are limits to this. Linck and Britz (1990) has shown that only bubbles with a diameter larger than 0.3 mm have sufficient buoyancy to push through the "elastic network" formed by the fibers in the suspension. Other studies have shown that bubbles with a diameter less than 0.1 mm tend to stick to the fibers, causing high fiber losses during flotation (Isler, 1978). This non-selective process is the principle behind dissolved air flotation clarifiers (DAF) which create air bubbles by depressurization of air dissolved in water to remove solids (Clark, 1985). In practice, these effects mean that bubble diameters of 1mm should be targeted and diameters smaller than 0.5 mm should be avoided.

Figure 3.11 shows a schematic representation of different size ink particles with respect to a 1 mm diameter bubble at the same scale. Due to the radius of curvature of the bubble, the ratio of contact area to ink particle surface area reduces with increasing ink particle size. For example, particles 10 and 50 microns in size particles adhere well. For particles 100 microns and larger, however, adherence becomes a problem since the bubble contour can no longer adapt itself to the contours of large particles. This indicates that if the particles to be collected are too big for the size of the bubble, the high turbulence in some flotation units will dislodge the particle from the surface of the bubble. In other words, for removing large particles, large air bubbles and quiescent conditions are required. Data from mineral flotation research indicates that the optimum bubble size is five times that of the particle being removed (Szatkowski and Freyberger, 1985). Therefore in order to be efficient in collecting a range of ink of particle sizes, the flotation process requires a wide range of bubble sizes.

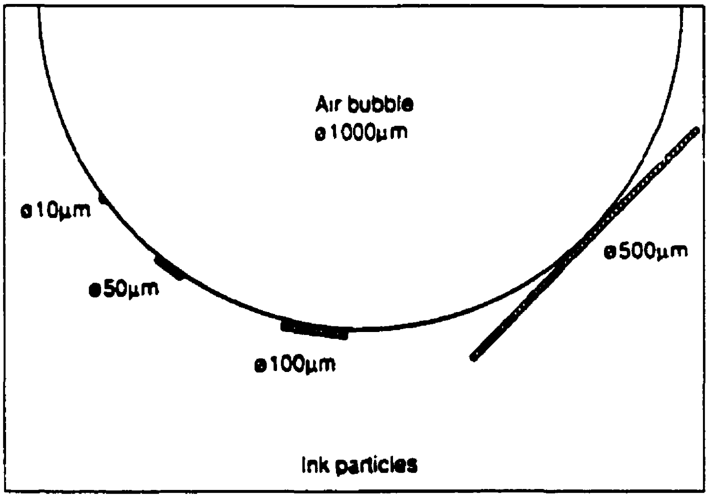


Figure 3.11 Model of contact surfaces.

Gases other than air have been examined for their effectiveness in flotation. Marchildon et al. (1991) looked at carbon dioxide, oxygen and nitrogen as flotation gases with newsprint furnish. They detected no significant change by using nitrogen or oxygen when compared to air, but they did notice a reduction in strength properties due to fiber degradation in the acid environment when using carbon dioxide.

3.5.2.5 Role of Mixing

It is essential to have good contact between the ink-laden grey stock and the air bubbles. Good contact is a function of the cell design and time. Forces acting on ink particles are complex, but they determine if collisions result in the formation of an ink particle/bubble complex. Good mixing is essential, but air bubbles must be allowed to rise to the surface, for removal of the attached ink. Long retention times also increase the probability of good particle/bubble contact, retention times vary from 5 to 20 minutes depending on the type of flotation cell.

3.5.2.6 Role of Equipment

The selection of flotation cell for a particular application is based on a number of factors. Apart from brightness gain across the flotation cell, important factors include, ink removal and fiber yield. Another critical parameter is the placement of the flotation cell in the deinking process flow sheet (Harrison, 1991, Zabala and McCool, 1988). If the cell is placed mid-way through the process it will have a broader range of particle sizes in the feed stock than if the cell is placed after the disperger where the particle sizes will be much smaller. Placement of the cell in the system can also dictate feed consistencies, pH and temperature. Available space can also be a factor in retrofitting flotation cell circuit in existing mills.

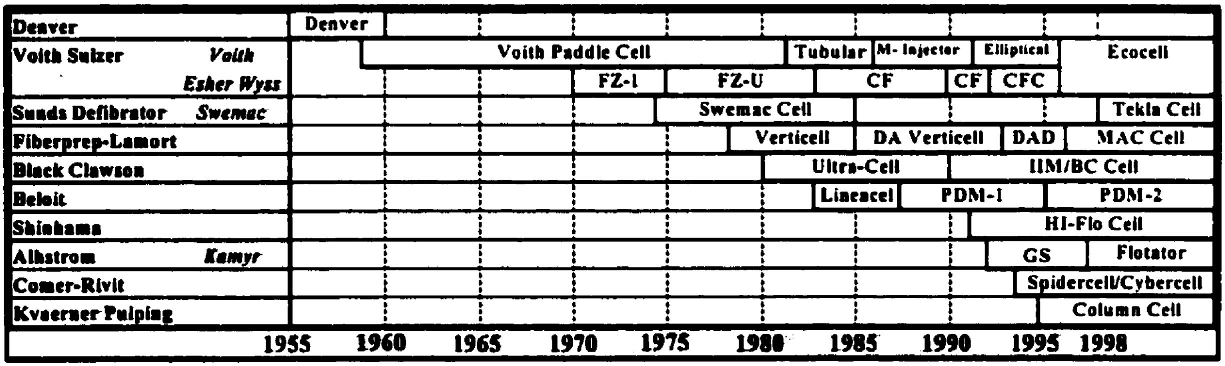
3.6 FLOTATION DEINKING TECHNOLOGY

Today, it is recognized that the flotation process is one of the most important sub-systems in a waste paper recycling mill, as it provides a low cost and effective means of removing ink particles from recycled pulp. The performance and operation of this subsystem is critical for producing the highest quality product at the lowest cost (Dessureault et al. 1995). This section will briefly describe the history of flotation cells used for deinking wastepaper and introduce seven modern flotation units that are currently available in North America.

3.6.1 History of Flotation Deinking

A brief history of the development of different flotation cells is summarized in Table 3.3. The major suppliers of flotation cells are shown on the left side of the chart and the year is shown across the bottom.

Table 3.3 History of flotation deinking cells (modified from McCool, 1993).



The development of deinking flotation cells has been an evolutionary one starting with a transfer of the Denver cell from the mineral processing industry in the 1950s. It can be seen that the pace of major developments has increased since the end of the 1970s.

3.6.2 Voith Sulzer - EcoCell

Until 1994, Voith and Escher Wyss were independent companies which supplied competitive flotation cells to the industry. Voith had been developing its injector cell technology since the early 1980s while Escher Wyss had been developing their line of Compact Flotation Cells (CFC) since 1983. In 1994, these two companies merged and became known as Voith Sulzer. In 1996 they combined their flotation technology and introduced the EcoCell flotation machine (Eriksson and McCool, 1997). This new cell utilized step diffuser air mixing technology from Escher Wyss and the quiescent elliptical cell geometry from Voith. A cross section and a mill installation of the EcoCell are shown in Figure 3.12.

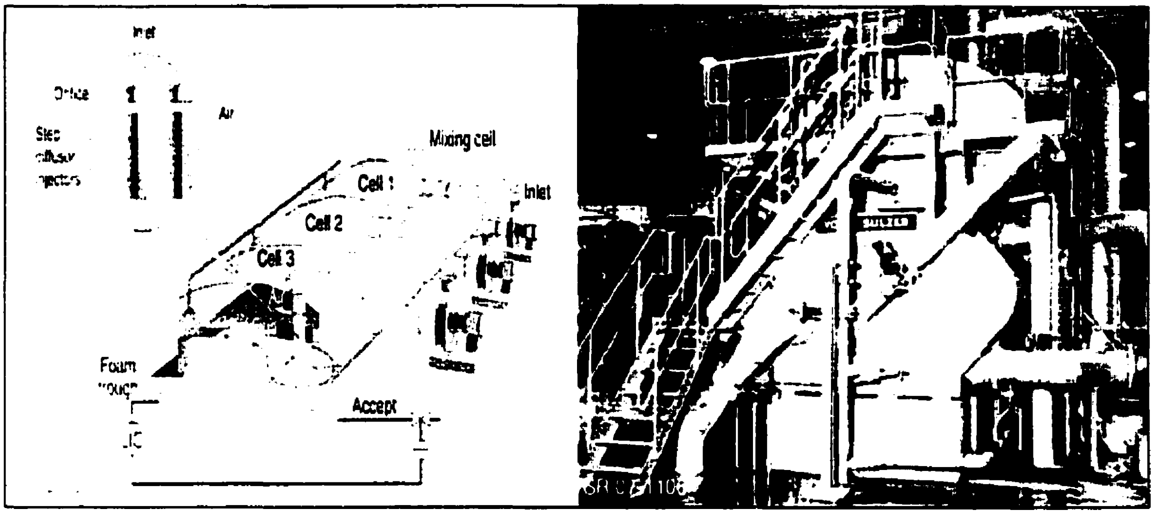


Figure 3.12 Voith Sulzer EcoCell (Reprinted by permission of Voith Sulzer).

Each cell, depending on the designed production capacity, has between one and four aeration elements. Air is drawn into the aeration element by a venturi effect. The EcoCell aeration elements consist of a nozzle plate with air suction apertures, a step diffuser block, an impact mixer and a distributor diffuser all designed to optimize the mixing of air bubbles and pulp (Martin and Britz, 1996). In the Voith EcoCell flotation system there are usually 3 to 6 primary cells and 1 to 2 secondary cells depending on the total ink removal required. In the primary cells the inky froth is usually removed by gravity overflow from each of the stages. The rejects from all the stages are collected and combined to feed the secondary cell. Mechanical scrapers remove foam from the secondary cell stages. For difficult to remove froths, a vacuum device known as the FothVac is used to break them down.

3.6.3 Fiberprep/Lamort - MAC Cell

In 1995, Fiberprep/Lamort introduced the MAC cell (FiberPrep, 1996). A cross section of this cell is shown in Figure 3.13. Essentially, the MAC cell is a tower of three to five stages of flotation. The feed to the first stage is aerated using special canisters called Autoclean injectors and then fed near the top of the cell. The inky froth rises to the surface and the accepts are removed at the center of the cell. The accepts from this stage are then aerated and returned to feed the cell below the first stage. This process continues three more times until a total of five aerations have been completed. Air is added to the various recirculation streams through special non-plugging injectors which induce air into the system. The system is totally enclosed to recycle the air and prevent potentially harmful fumes entering the mill atmosphere. Reject discharge is controlled through a slight overpressure inside the cell and only rarely is a secondary stage required.

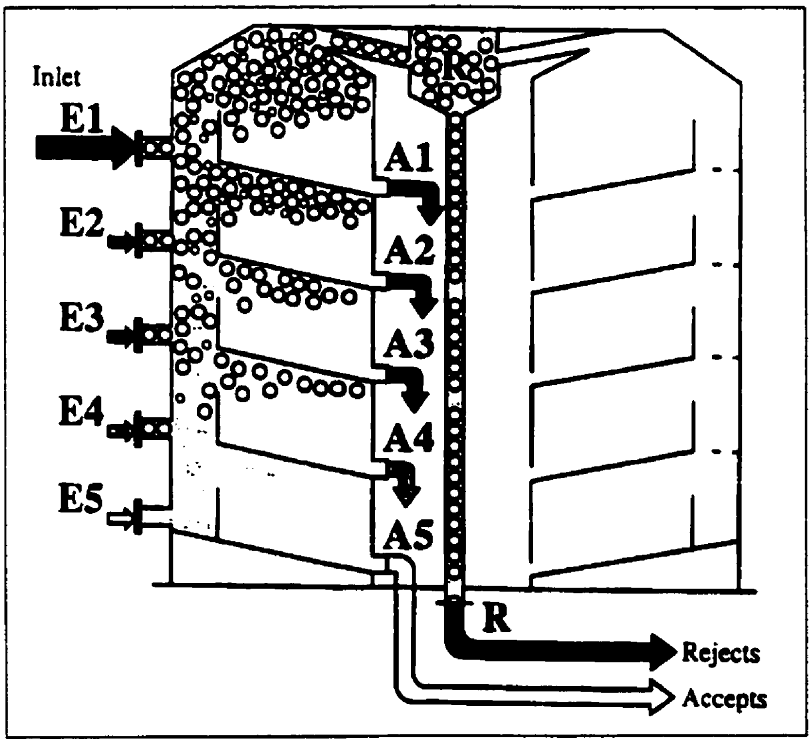


Figure 3.13 FiberPrep-Lamort MAC cell (Reprinted by permission of FiberPrep-Lamort).

3.6.4 Black Clawson - IIM-BC Flotator Cell

The IIM-BC Flotator is based on Japanese technology and was introduced to North America by Black-Clawson in 1990. A cross section of the cell is shown in Figure 3.14. The Flotator consists of a large vessel with rounded corners and has a large volume (50 m^3) (Black Clawson, 1996). Stock is fed in at the bottom, and the accepts leave the cell at the opposite corner. Two special turbines, each with an air manifold, are located in the bottom and run the length of the cell. Compressed air is fed to these rotating turbines which mix the air thoroughly to create fine bubbles and to circulate the stock. Internal baffles direct the flow of pulp so it passes the turbines a number of times. This design incorporating small bubbles is reported to successfully handle difficult to deink 100 % newspaper feed, as well as small flexographic ink particles (Gilkey et al., 1994). Air bubbles rise to the surface generating a froth which is removed by a series of scrapers.

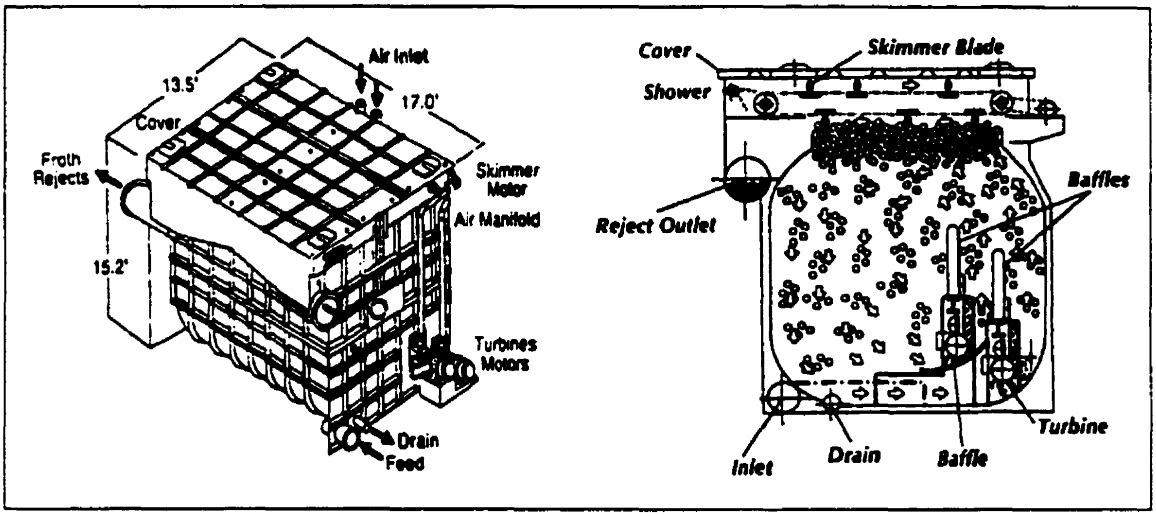


Figure 3.14 Black Clawson IIM-BC Flotator (Reprinted by permission of TAPPI, Copyright 1993, published in Secondary Fiber Recycling).

A high froth depth is maintained at the top of the cell to give low reject consistencies and reduced fiber loss. Other features of this cell include long retention times (10-15 minutes) and high air addition rates of 600 to 1000 % of the feed volumetric flow rate (Seifert, 1994). Because of the long retention time complete flotation is usually achieved in one stage although at low capacity. The consequence of this is that a Flotator system consists of a number of cells in parallel rather than in series (i.e., 5 cells in parallel for a 300 tonne/day operation).

3.6.5 Beloit - PDM Cell

In 1987 Beloit introduced the PDM flotation cell. The name PDM denotes "Pressurized Deinking Module". In North America there are now over 10 installations of PDM technology with the first being built at Desenscrage Cascade near Quebec City, Canada. This was a radical departure from the traditional designs since the PDM was the first flotation cell to operate under pressure. In 1995 Beloit modified the PDM and it is now known as the PDM-2. These modifications include internal engineering changes to enhance the froth removal system and flotation efficiency of the cell (Milliken, 1997). As shown in Figure 3.15, the design of the two PDM cells has physically separated each of the principal stages of flotation, pulp aeration, bubble/particle attachment and bubble/pulp separation.

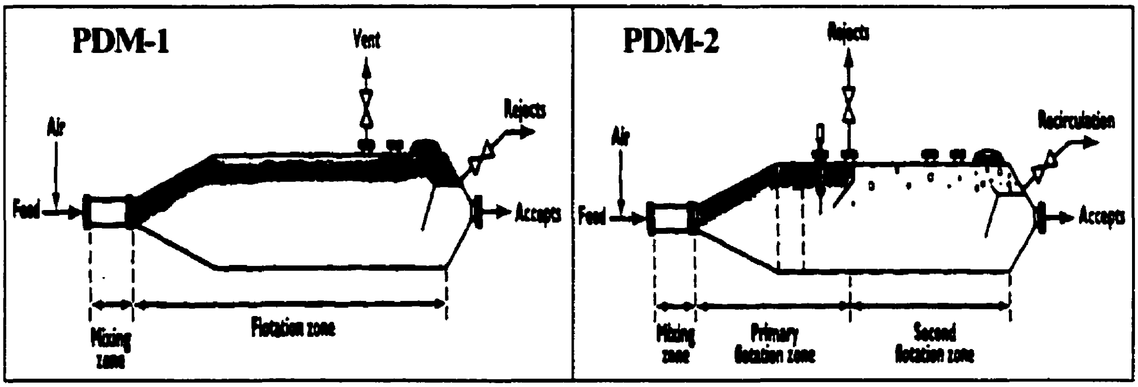


Figure 3.15 Beloit PDM-1 and PDM-2 flotation cells (Originally published in TAPPI JOURNAL, Vol. 80, No. 9., Copyright TAPPI 1997).

In the aeration zone (before the mixing zone), air is injected under pressure and can be adjusted to account for the incoming furnishes and chemistry used. A highly turbulent flow pattern in the mixing zone ensures excellent bubble/particle contact. Carroll and McCool (1990) report that the pressurized air used in the PDM causes some of the air to be dissolved into the pulp which may nucleate on ink particles. In the separation zone, the flow velocity is reduced so that the air bubbles will rise to the surface. Ink laden froth is removed by adjusting the reject weir valve opening. The normal operating pressure of the flotation cell expels the reject froth while the valve is open. In a similar way, the pressure also pushes the recirculation stream out of the recirculation valve. The recirculation stream was added to the design because it was realized that small bubbles were passing through the system with the accepts stream. This stream is returned to the flotation cell feed chest for a subsequent pass through the process without fiber loss (Carrol and McCool, 1990). Depending on the application there can be one to four primary stages. No secondary stages are normally required.

3.6.6 Kamyr/Ahlstrom - GSC Cell

The gas sparged cyclone (GSC) was originally developed by J.D. Miller at the University of Utah for mineral applications. Ahlstrom/Kamyr developed the unit for deinking applications in 1990 (Figure 3.16). The GSC has a residence time of a few seconds and is capable of performing flotation at consistencies ranging from less than one to greater than three percent. The waste paper stock is introduced tangentially to the body through a typical cyclone inlet, resulting in a rotating stock flow. The air is sparged through a porous polymer-based wall (average pore size 5-200 μm) to form small bubbles. The porous wall combined with the shearing action of the stock as it passes through the GSC generate a suitable bubble size range (Chamblee and Greenwood, 1991).

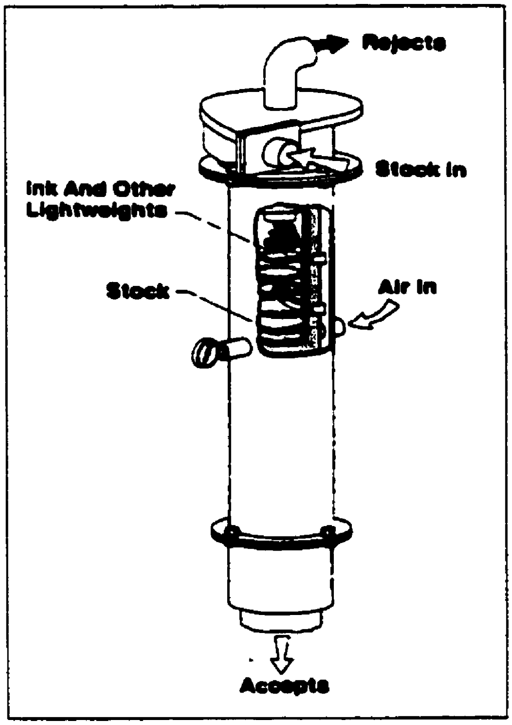


Figure 3.16 Gas sparged cyclone flotation cell (Reprinted by permission of TAPPI, Copyright 1993, published in Secondary Fiber Recycling).

Ink particles attach to the bubbles, which along with lightweight contaminants, are forced to pass through the rotating stock to the center of the GSC due to centrifugal forces. The foam containing the ink and light weight contaminants, flows upwards to a vortex finder where it is removed. The accepts are removed from the bottom of the GSC. Individual GSC units are arranged in banks similar to ordinary cyclones and each unit has a capacity of 20-30 tpd at 1.5 % consistency.

3.6.7 Comer-Rivit - Spidercel

Comer-Rivit introduced the Spidercel deinking unit to North America in 1994. A cross section of the cell is shown in Figure 3.17. The Spidercel has been tested on various furnishes including paper with laser and UV inks. Stock is fed to the bottom of the unit and is distributed to a series of high-velocity nozzle-type venturi injectors for aeration and mixing into the body of the cell.

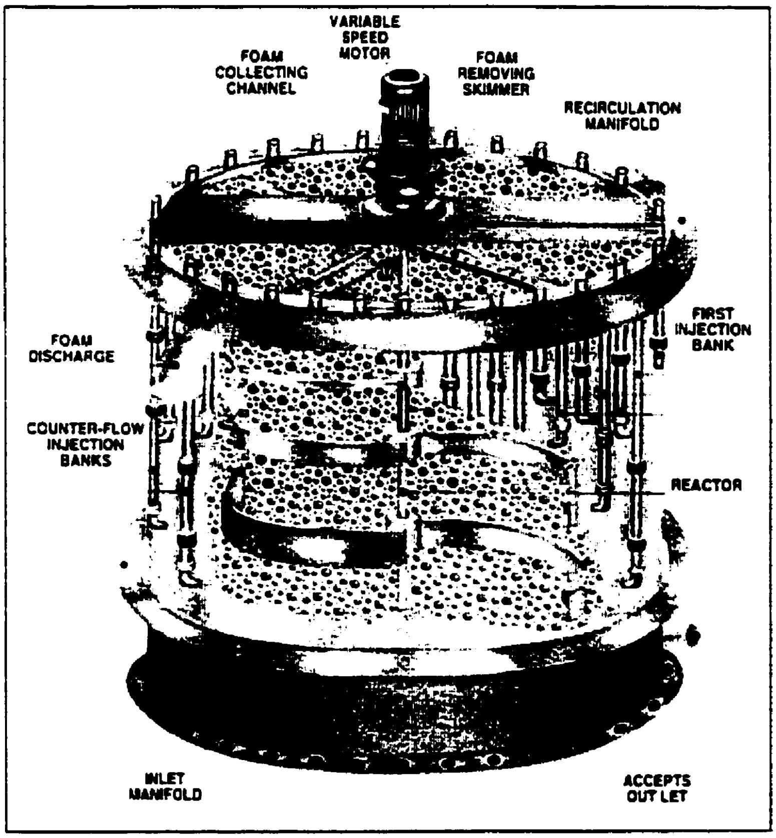


Figure 3.17 Comer-Rivit SpiderCel deinking cell (reprinted by permission of Comer-Rivit).

Within the cell there is a centrally located mixer which enhances the rise of bubbles to the surface. Accepts are returned near the bottom of the cell for secondary treatment with a second ring of venturis. Each venturi level has been designed to provide varying bubble sizes for removal of inks and contaminants over a wide range of particle sizes (Comer-Rivit, 1998). Ink-laden froth is removed with a scraper and discharged through an overflow trough. In a mill installation there are normally two cells in series with no secondary cells to recover lost fibers. Recently, Comer Rivit has introduced a new version of the Spider Cell called the CyberCel. This cell includes a more sophisticated rotating mixer with slotted discs which control the rising air velocity and bubble size. The manufacturer claims that this improvement results in only one cell being required for all deinking applications instead of two.

3.6.8 Kvaerner Pulping - Flotation Column Cell

Kvaerner Pulping (Formerly Kvaerner Hymac) entered the flotation deinking market with the flotation column in 1992 based upon technology developed by the mineral processing industry. A cross-section of column used for deinking waste paper is shown in Figure 3.18. Preliminary results from studies based on this system indicate low fiber losses and low capital costs (Dessureault et al. 1995).

In this unit, the stock is fed about one third from the top and flows down where it meets a rising swarm of bubbles generated by porous metal spargers at the bottom of the column. Ink particles become attached to the air bubbles in the mixing zone and rise to the top of the cell where the ink-laden froth is removed by a scraper. Traditionally flotation columns in the mineral industry utilize water sprays at the top of the column to wash entrained gangue particles from the froth. This concept does not seem to be utilized in the Kvaerner design. Baffles are installed inside the column to try to achieve plug flow transport of the pulp. Kvaerner Pulping claim that the unit is highly effective in collecting a wide range of particle sizes and that only one flotation stage is typically required (Kvaerner Pulping, 1997).

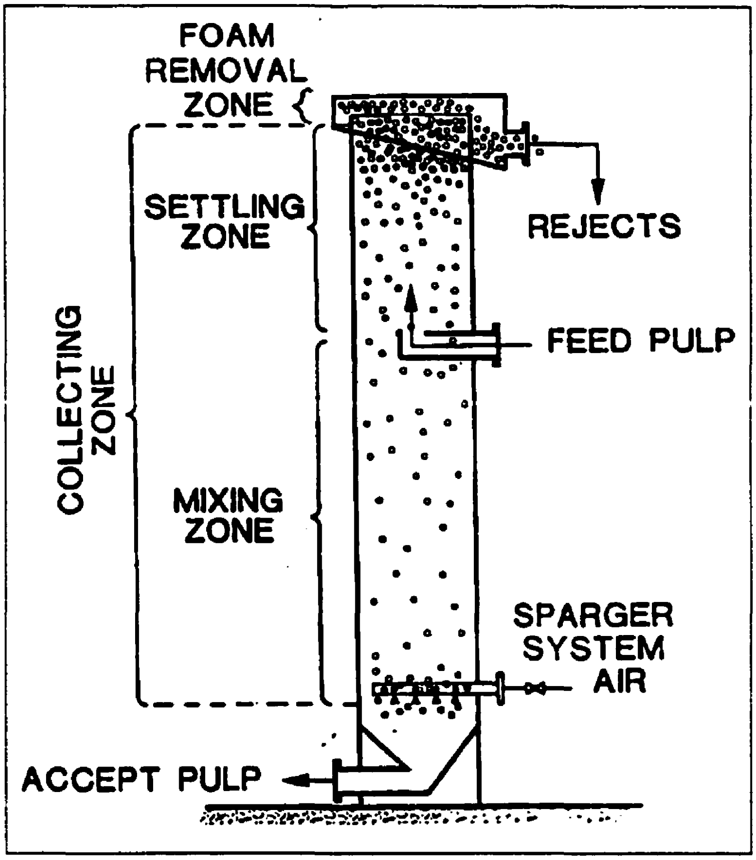


Figure 3.18 Kvaerner Pulping flotation column (Reprinted by permission, Copyright, Doshi & Associates., Inc, P.O. Box 2771, Appleton, WI 54913-2771).

3.7 SUMMARY

Waste paper recycling is growing rapidly in Canada. The method by which ink is applied to paper determines its recyclability. The most important deinking mechanism in todays recycling mill is froth flotation. Flotation deinking is employed to rid waste paper stock of unwanted particulates such as ink and ash. There are four principal factors that affect flotation deinking: pulp chemistry, the size and nature of the particle to be removed, the size and nature of the bubbles and the design of the flotation cell. The design philosophy of deinking cells is wide ranging, as demonstrated by the examples. Despite the differences in design, each flotation cell has three elements in common: aeration, mixing and separation zones. The similarities and differences help to illustrate that there remains much work to be done on understanding the fundamentals of what is required for ink removal.

❖ CHAPTER FOUR ❖

Theoretical Principles

4.1 INTRODUCTION

In a conventional flotation column, feed slurry enters near the top of the column and flows counter-current to a rising swarm of bubbles. The air bubbles, generated by a sparging device at the bottom of the column, collect floatable particles and carry them to the froth at the top of the column. Unique to columns is their ability to eliminate entrained particles from the froth by the use of wash water added to the top of the column. This cleaning action results in a high degree of selectivity as the recovery of non-hydrophobic particles to the overflow is minimized. Other advantages of flotation columns in comparison to conventional mechanical cells in the mining industry are less floor space requirements, reduced capital costs, adaptability to automated control and reduced operating and maintenance cost due to the lack of moving parts (Wills, 1992).

4.2 COLUMN FLOTATION DESIGNS

Many different types of column cell configurations exist; however, only the internally aerated conventional column and the externally aerated Microcel^{TM} column will be discussed. All terms and definitions are referenced from Finch and Dobby (1990) unless otherwise specified.

4.2.1 Conventional Flotation Column

A schematic diagram of the conventional flotation column is shown in Figure 4.1. Feed (F) enters near the top and flows down the column while gas bubbles rise from the internal spargers at the bottom. The bubbles collect floatable particles, giving the name collection zone (H_c). Froth forms in the top section through which wash water (W) flows. Wash water stabilizes the froth and replaces the water which naturally drains from it. The remainder of the wash water flows through and cleans the froth of particles entrained in the water crossing with bubbles from the collection zone. Therefore, the froth zone is also called the cleaning zone (H_f). The flow of water through the froth is called bias water (B), a positive value corresponding to a net flow downwards. For efficient cleaning of entrained particles the bias rate must be positive.

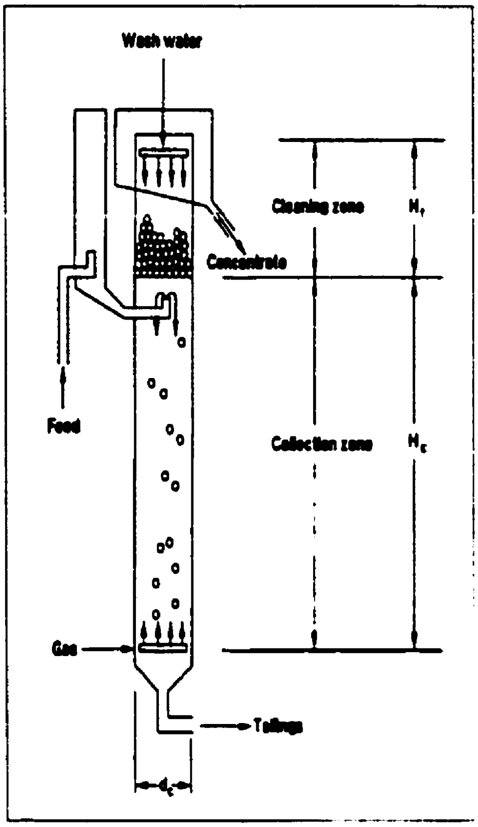


Figure 4.1 Conventional flotation column with internal sparging system. (Finch and Dobby, 1990)

The height of the collection zone, H_c, is defined from the spargers to the interface level, and the froth height H_f is defined from the interface to the overflow level. The column diameter is d_c. In deinking which is a reverse flotation process, the overflow product is termed the rejects (R), as it consists primarily of the undesirable materials, such as printing inks, stripped from the feed. The underflow stream (A) is termed the accepts, as it contains the cleaned pulp.

The most common internal spargers for flotation columns are fabricated from filter cloth or perforated rubber tubes. The major disadvantage of these spargers is that they generate relatively large bubbles, often larger than 2 to 3 mm. Porous metal and permeable ceramic tube spargers have become more popular due to their ability to produce small air bubbles, but they are prone to plugging and must be frequently removed and cleaned. This is a time-consuming process, which sometimes requires the column be removed from service.

4.2.2 Microcel™ Flotation Column

The Microcel™ flotation column was originally developed by researchers at the Center for Coal and Mineral Processing (CCMP), Blacksburg, Virginia USA. It is now sold and marketed by Process Engineering Resources Inc. (PERI) of Salt Lake City, Utah USA. This column is the same as a conventional column with the exception of the air sparging system, which incorporates a novel external bubble generation device, known as the Microcel™ bubble generator (Figure 4.2). The Microcel™ column is operated in the same manner as the conventional column and the terms used to describe it are identical.

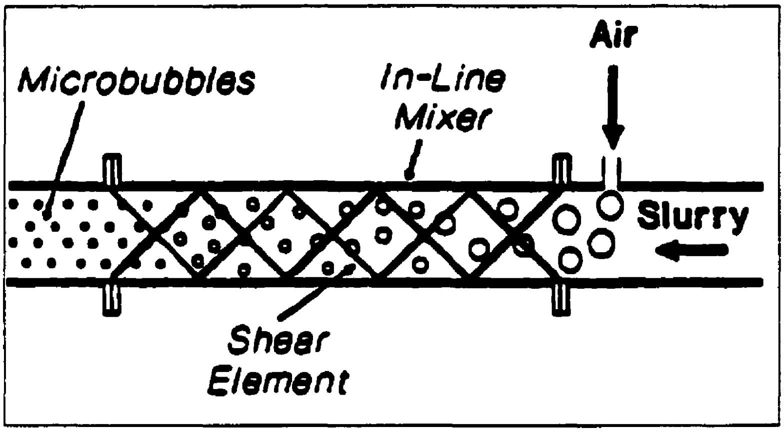


Figure 4.2 Microcel™ bubble generator.

In the Microcel™ system, air dispersion is achieved by using a centrifugal pump to circulate a portion of the pulp from the lower section of the column through a set of in-line static mixers (Figure 4.3). Controlled amounts of air and frother are introduced into the pulp just ahead of the mixers. As the mixture passes through three to six stationary blades located within the mixer, the air is sheared into very small bubbles by the intensive agitation. This configuration is capable of producing suspensions containing bubbles typically of less than 1 mm in diameter. The bubble suspension enters through the side of the column, where the air bubbles are allowed to escape and rise upward to collide with particles.

The reported technical advantages of the Microcel™ column are (Brake et al., 1996): 1) Reliable scale-up of the air sparging system; 2) Higher flotation kinetics due to smaller bubbles; 3) Reduced air consumption; 4) More energy efficient than other columns; 5) Reduced column height; 6) Reduced maintenance; and 7) Scavenging action of sparger.

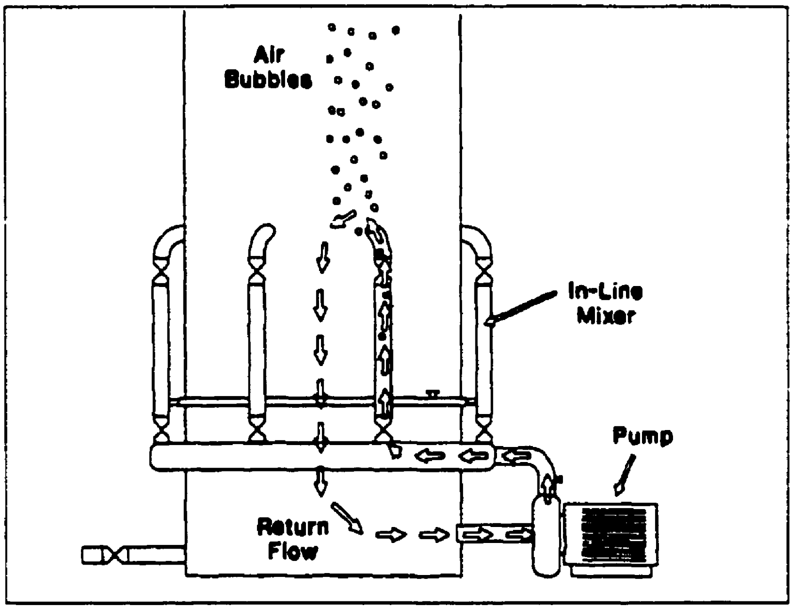


Figure 4.3 External Microcel^{TM} sparging system (Brake et al., 1996)

4.3 TERMS AND DEFINITIONS

4.3.1 Flow Rates

In column flotation, flow rates can be expressed in a number of ways. In this work, mass flows will only be used for recoveries and material balances. Superficial velocities are used to define gas and liquid rates. Superficial velocities are useful because they can be used to compare the operation of columns with different diameters. For any fluid (i), its superficial velocity (J) is given by the volumetric flow rate (Q) divided by the column cross sectional area.

$$J_i = \frac{Q_i}{A_c} \tag{4.1}$$

The fluids (i) can be liquid (l) or slurry (sl) in general, gas (g), feed (F), accepts (A), rejects (R), wash water (W), or bias water (B). The quotient has units of, for example, (cm^3/s)/(cm^2), to give units of velocity, cm/s. Because air is compressible, Q_g and thus J_g are a function of vertical position in the column. A given mass of air rising through the column will exhibit a greater volumetric flow rate at the top of the column where the static pressure is the least. Unless otherwise specified, all gas rates in this work are corrected to half way between pressure transducers.

4.3.2 Gas Holdup

The introduction of gas into a column results in the displacement of the liquid (or slurry) present. Gas holdup (ε_g), is the volumetric fraction of displaced liquid. Gas holdup is useful in determining the flow regime in the collection zone and is essential for techniques used in this thesis to estimate bubble size, bubble surface area rate and pulp retention time. These terms are defined in future sections. Pressure transducers or manometers can be used to determine gas holdup and detect axial variations in gas along the column.

The pressure difference method can be used to measure local gas holdup in the column. In this method, the local section is defined as the distance between pressure tapping points (Figure 4.4). The pressure at A and B is given by:

$$P_A = \rho_{sl}\, g\, L_A(1-\varepsilon_{gA}) \tag{4.2}$$

$$P_B = \rho_{sl}\, g\, L_B(1-\varepsilon_{gB}) \tag{4.3}$$

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

$$\Delta P = \rho_{sl}\, g\, \Delta L(1-\varepsilon_g) \tag{4.4}$$

assuming that $\varepsilon_{gA} = \varepsilon_{gB} = \varepsilon_g$. The gas holdup between A and B can then be found by rearranging the former equation into the following form:

$$\varepsilon_g = 1 - \frac{\Delta P}{\rho_{sl}\, g \Delta L} \tag{4.5}$$

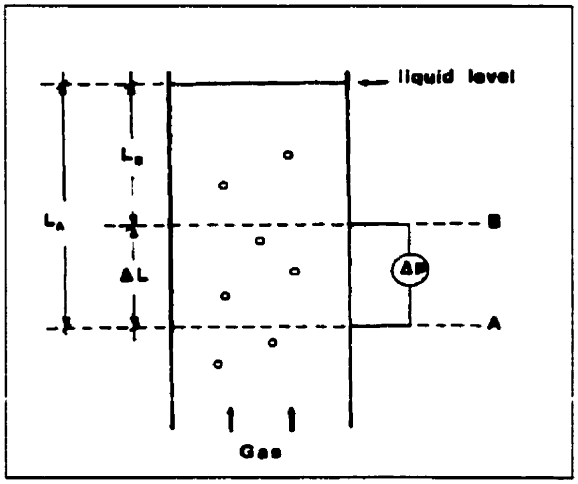


Figure 4.4 Measurement of gas holdup by pressure difference (Finch and Dobby, 1990).

4.3.3 Column Flow Regimes

The flow regime in the collection zone can be described from the relationship between ε_g and J_g (Figure 4.5) (Shah et al., 1982). Gas holdup increases approximately linearly and then deviates at some superficial gas velocity (J_g) ranging from 1 to 4 cm/s depending on the pulp and chemical characteristics.

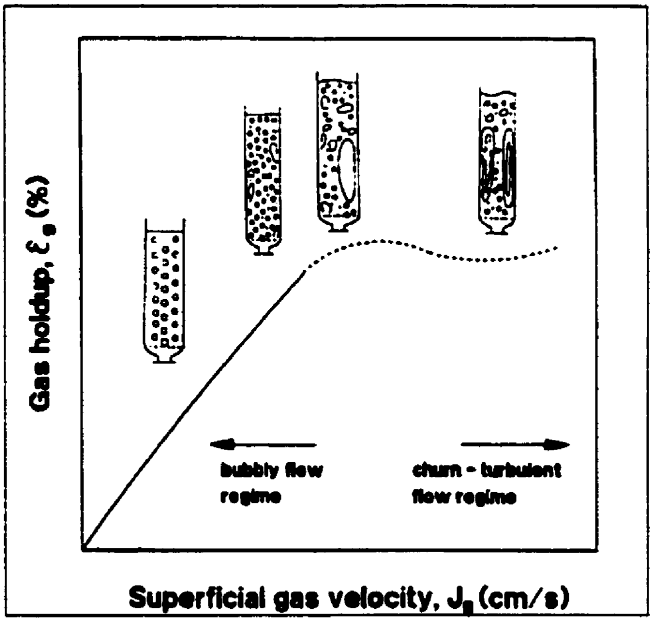


Figure 4.5 General relationship between gas rate and gas holdup (Finch and Dobby, 1990)

The relationship shown in the figure is for a particular downward slurry velocity. If J_{sl} were increased, the line would shift up and increase in slope. At a given J_g, an increase in J_{sl} would slow the bubble rise velocity, increasing gas holdup. Adding a surfactant (to keep d_b small) would have a similar effect. At a given J_g and J_{sl}, smaller bubbles rise at a slower rate, and the result is an increased gas holdup.

Operation in the bubbly flow regime is recommended for column flotation. This is characterized by quiescent conditions and a relatively uniform bubble size. Churn turbulent conditions occur when an increase in J_g does not give a corresponding increase in ε_g. This flow regime is characterized by large bubbles (slugs) rising rapidly, displacing water and small bubbles downward. Operation in this flow regime usually involves loss of interface between the collection zone and froth zone, and a loss of positive bias. Increasing the slope in figure cause the churn-turbulent transition point to shift back to lower J_g values. In other words, increasing J_{sl} or decreasing d_b reduces the maximum J_g at which bubbly flow can be maintained. By extension, at a given J_g and d_b, there is a maximum J_{sl} for bubbly flow, and at a given J_g and J_{sl}, there is a minimum d_b for bubbly flow.

4.3.4 Superficial Bubble Surface Area Rate

The constraints imposed by the J_{sl}, J_g and d_b to maintain bubbly flow also place limits on the processing and ink removal capacities of the column. Since in flotation, solid particles are collected by air bubbles, the particle removal rate of a particular device can be related to the superficial bubble surface area rate (S_b) it produces. S_b is defined as follows:

$$S_b = \frac{Q_g}{A_c}\left(\frac{SA_b}{V_b}\right) = \frac{6 \cdot J_g}{d_b} \tag{4.6}$$

where SA_b is the surface area of the bubble, V_b is the volume of the bubble, d_b is the diameter of the bubble and A_c is the column cross sectional area. S_b has units of bubble area rate per unit area of column (cm^2/s)/cm^2) or simply (s^{-1}). An alternative term is bubble surface area flux (BASF).

4.3.5 Drift Flux Analysis

To determine the bubble surface area rate it is necessary to know the bubble size. Drift flux analysis can be used to determine bubble diameter from readily measured data such as ε_g, J_g and J_l. This proves very useful in opaque columns or for opaque slurries, where bubble diameters cannot be measured photographically. The concept of drift flux analysis was originally introduced by Wallis in 1969 and has been applied to both two and three phase systems. The mean bubble diameter in a bubble swarm can be calculated using a number of methods, however, all of them make use of some standard equations (Banisi and Finch,1994).

For a flotation column operating with counter-current flow the relative slip velocity (U_{sb}) between the gas phase and the liquid phase is defined as:

$$U_{sb} = \frac{J_g}{\varepsilon_g} + \frac{J_l}{(1-\varepsilon_g)} \tag{4.7}$$

The slip velocity is related to the single bubble terminal rise velocity in an infinite pool U_t and gas holdup ε_g by the following equation assuming:

$$U_{sb} = U_t (1-\varepsilon_g)^{m-1} \tag{4.8}$$

where m is related to the bubble Reynolds number Re_b and column diameter d_c (Richardson and Zaki, 1954):

$$m = \left(4.45 + 18\frac{d_b}{d_c}\right)\mathrm{Re}_b^{-0.1} \qquad (1 < \mathrm{Re}_b < 200) \tag{4.9}$$

$$m = 4.45\,\mathrm{Re}_b^{-0.1} \qquad (200 < \mathrm{Re}_b < 500) \tag{4.10}$$

And

$$\mathrm{Re}_b = \frac{U_t \rho_f d_b}{\mu_f} \tag{4.11}$$

Combining equations (4.7) and (4.8) and rearranging yields:

$$U_t = \frac{J_g}{\varepsilon_g (1-\varepsilon_g)^m} - \frac{(J_g + J_l)}{(1-\varepsilon_g)^m} \tag{4.12}$$

The standard equation for the terminal rise velocity of a sphere is:

$$U_t = \left(\frac{4g\Delta\rho d_b}{3\rho_f C_D} \right)^{0.5} \tag{4.13}$$

where C_d, the drag coefficient, can be calculated using an approximation proposed by Schiller and Naumann (1933) for Re_b less than 800:

$$C_D = \frac{24}{\mathrm{Re}_b}\left(1 + 0.15\mathrm{Re}_b^{0.687}\right) \tag{4.14}$$

Re-arranging the former two equations gives the bubble diameter in a bubble swarm:

$$d_b = \left[\frac{18\mu_f U_t}{g\Delta\rho}\left(1+0.15\mathrm{Re}_b^{0.687}\right) \right]^{0.5} \tag{4.15}$$

where U_t is obtained from Equation (4.11) and where according to Xu and Finch (1990):

$$\mathrm{Re}_s = \frac{d_b U_s \rho_f}{\mu_f} \tag{4.16}$$

Equations (4.7) through (4.16) inclusive provide the basis for the drift flux model. This model can be used in a number of ways to extract information from real systems. Typically J_g, J_l and the physical properties (μ,ρ) are known. The experimental bubble sizes calculated in this thesis were obtained by the rederived Finch and Xu method (Banisi and Finch, 1994). In this method m is set to 3, d_b is estimated, and then U_{sb}, Re_s and U_t are used to produce a calculated bubble diameter. The following is a step by step procedure:

1) Let m=3
2) Estimate d_b
3) Calculate U_{sb}, equation (4.7)
4) Calculate Re_s, equation (4.16)
5) Calculate U_t, by equations (4.8) and (4.15); then iterate on d_b.

4.4 COLLECTION ZONE

4.4.1 Particle Collection

In this discussion, particle will refer to ink, ash or fiber which all can be recovered to the column rejects stream. The most important physical and chemical conditions necessary for the efficient flotation of ink were described in Section 3.5.2. In flotation deinking particles can be collected as a result of favorable surface properties, as a result of hydrodynamic entrainment, or by entrapment of bubbles which buoy the particles upward.

The first mechanism is important because it is selective for ink flotation. Hydrophobic ink agglomerates collide with and attach to air bubbles. In some cases however, it has been postulated that fibers are also floated by this mechanism. Studies by Turvey (1993), Galland et al. (1977), and Larsson et al. (1982) have shown a positive correlation between fiber loss and calcium content of the pulp. This has led to several theories on how the presence of calcium effects fiber hydrophobicity. For example Larsson et al, propose that the fibers become hydrophobic in the presence of calcium due to the formation of "large, soap-ink flocks" which re-precipitate on the fiber. Turvey suggests that the calcium forms a hydrophobic complex with the dispersed print particles.

The second mechanism is not selective. Particles are collected and recovered to the froth zone by entrainment in the wake of rising bubbles. Entrainment is extensively documented in the literature in mineral flotation systems (Warren, 1985; Kawatra and Eisele, 1991; Hemmings, 1980; and Maachar and Dobby, 1992). This mechanism accounts for the presence of hydrophilic gangue in the froth, and for the presence of fine particles (both hydrophobic and hydrophilic) that are too small to be recovered by conventional flotation. This potentially significant pulp loss mechanism has received little attention in flotation deinking until fairly recently Petri (1994), Dorris and Page (1997), Deng and Abazeri (1998) and Ajersch and Pelton (1996).

The third mechanism is proposed for fiber recovery to the rejects (Pelton and Piette, 1992). Depending on the bubble size and pulp consistency fibers can form networks or flocs while in suspension. Small bubbles rising without enough force to break through the network of fibers can become trapped within them. The entrapped air reduces the bulk density of the fiber networks, which enables them to float. The entrapment is mechanical; there is no attachment. Factors effecting this phenomena include consistency and fiber length (Wahren, 1979) and flow conditions, such as the level of shear (Kerekes, 1983).

The goal of flotation is the collection of hydrophobic particles by attachment to air bubbles. Minimizing the other possible flotation mechanism is the key to selectivity. Much of the success of flotation columns results from their ability to minimize entrainment of hydrophilic particles. Collection by air bubbles results from the collision of particles with bubbles, followed by attachment. 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 a bubble. For a collection zone with air bubbles of diameter d_b rising at a rate J_g through a liquid with a concentration of particles c_p, the rate of particle removal is given by (Finch and Dobby, 1990):

$$\frac{dc_p}{dt} = \frac{1.5 J_g E_K c_p}{d_b} \tag{4.17}$$

This is equivalent to the first-order rate process with rate constant k_c given by:

$$k_c = \frac{1.5 J_g E_K}{d_b} \tag{4.18}$$

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

$$R_c = R_{eq}\left[1 - \exp\left(-k_c \tau_p\right)\right] \tag{4.19}$$

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 must be modified to account for mixing. Collection efficiency can be expressed in terms of the efficiencies of its two sub-processes, collision efficiency (E_C) and attachment efficiency (E_A):

$$E_K = E_C E_A \tag{4.20}$$

Particle detachment is not considered important because it has been found to be minimal for particles less than 100 um in deinking systems. Equations (4.17 and 4.18) are important because they relate the collection rate constant and the collection efficiency to important system variables such as gas rate and bubble size. Reducing bubble size can enhance flotation rates by increasing E_K (which increases K_c). However it was shown in sections 3.5.2 and 4.3.3 that there was a minimum bubble size constraint, so E_K and K_c are also limited by $d_{b,min}$.

4.4.2 Mixing

Mixing in the collection zone of a flotation column is an important parameter for scale-up. As mentioned before, laboratory columns with large Hc/dc ratios, exhibit plug flow conditions (Section 4.4.1). The plug flow model assumes perfect radial mixing and no axial mixing. However, due to the counter-current contact of slurry and air, flow through the collection zone in industrial-scale columns is not truly plug flow but somewhere between those of plug flow and perfectly mixed flow. The recovery for particles in a perfectly mixed system is given by:

$$R_c = R_{eq}\left[1-(1+k_c\tau_p)^{-1}\right] \tag{4.21}$$

where k_c, τ_p and R_{eq} are the same as in equation (4.19). Mixing has a detrimental effect on recovery since some particles short circuit and have a reduced probability of encountering air bubbles.

The plug flow dispersion model can be used to describe the axial mixing process in the collection zone. It accounts for axial mixing and radial mixing is still assumed perfect. Under this model, recovery (R) is given by the following equation:

$$R = R_{eq}\left[1-\frac{4a\exp\left(\frac{1}{2N_d}\right)}{(1+a)^2\exp\left(\frac{a}{2N_d}\right)-(1-a)^2\exp\left(\frac{-a}{2N_d}\right)}\right] \tag{4.22}$$

where a is a simplifying term given by:

$$a = (1+4k_c\tau_pN_d)^{0.5} \tag{4.23}$$

The vessel dispersion number N_d accounts for axial mixing, and can be written in terms of the various system parameters:

$$N_d = \frac{0.063\, d_c \left(\frac{J_g}{1.6} \right)^{0.3}}{\left[\left(\frac{J_{sl}}{1-\varepsilon_g} \right) + U_{sp} \right] H_c} \tag{4.24}$$

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

$$\tau_p = \tau_l \frac{\frac{J_{sl}}{(1-\varepsilon_g)}}{\frac{J_{sl}}{(1-\varepsilon_g)} + U_{Sp}} \tag{4.25}$$

where τ_l is the liquid retention time and U_{sp} is the particle slip velocity which can be obtained from the following equation:

$$U_{sp} = \frac{g\, d_p (\rho_p - \rho_{wat})(1-\phi_s)^{2.7}}{18\, \mu_{wat} \left(1 + 0.15\, \mathrm{Re}_p^{0.687}\right)} \tag{4.26}$$

where the particle Reynolds number Re_p is:

$$\mathrm{Re}_p = \frac{d_p U_{sp} \rho_{wat} (1-\phi_s)}{\mu_{wat}} \tag{4.27}$$

and ϕ_s is the solid volumetric fraction. The preceding equations are the one dimensional plug flow dispersion model and are fundamental to the scale-up process which is described in section (4.6).

4.5 FROTH ZONE

Column froths are quite complex, over the height of the froth, gas holdup increases and bubble sizes increases. In general, there are three primary regions: 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 first region by colliding with the interfacial froth. This results in shock waves through the froth which cause bubble coalescence (increasing d_b). The liquid content in this region is generally greater than 25%. The next zone in the froth is the packed bubble bed and extends to the wash water inlet. The rate of coalescence is lower in this region than zone 1 and the bubbles are mostly spherical but range in size. In this region the liquid content is less than 25%. 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 region does not form. The main purpose of this region is to convert vertical motion into horizontal to recover the collected solids.

One of the most significant advantages of the flotation column is the ability to add wash water to the froth zone. Wash water provides the bias water and the water necessary to cause the overflow of recovered solids into the launder. Without wash water, the water in the froth (in a column or any other cell) must come from the feed slurry, along with its non-selective complement of entrained particles. Entrained particle recovery in columns has been found to be proportional to feed water recovery (Maachar and Dobby, 1992). The variables which affect the recovery of entrained particles or feed water are the gas rate, bias rate and froth depth. As J_g increases the concentration of feed water in the froth increases. In principle, the bias water supplied by clean wash water will eliminate entrained particles and result in high selectivity for hydrophobic particles. Wash water tends to promote froth stability and deeper froths which can accommodate surges in level and reduce entrainment in instances when high gas rates are used.

The froth zone in a column helps the flotation process approach its theoretical selectivity, not only for entrained hydrophilic particles by cleaning, but also for collected particles of differing hydrophobicity. Bubble coalescence and froth zone drop back enhance the selectivity between particles of differing hydrophobicity. In the upper reaches of the froth zone, bubble coalescence reduces the bubble surface area, and may result in particle detachment and reattachment within the zone. Particles with greater hydrophobicity have higher flotation rate constants, and will be selectivity removed if detachment and reattachment events repeatedly occur. Similarly with froth zone drop back, where recovered particles fall back to the collection zone, more hydrophobic particles with a greater flotation rate constant will be selectively recollected. Froth drop back is related to column geometry, and thus is important to scale-up. Walls add stability to froth, so in a laboratory column (small diameter), the froth zone drop back may be small. In a full size column, however, the reduced influence of the walls tends to increase the amount of froth zone drop back. Therefore, if not accounted for in the scale-up procedure, the overall column recovery will be less than calculated.

4.6 COLUMN FLOTATION SCALE-UP

Column scale-up methodology begins by specifying a target recovery for a component in the system being considered, along with the required feed rate. Manufacturers of flotation columns determine the size of the column and air sparging system using governing equations and other in house scale-up parameters. Laboratory or pilot -scale columns are typically used to collect "scale-up" data and to also determine whether column cells are suited to the required task.

4.6.1 Column Geometry

In order to correctly predict the geometry of a flotation column for a certain application the interaction between the collection zone and the froth zone must be accounted for. Figure 4.6 shows the relationship between the two zones where (R_c) in the collection recovery and (R_f) is the froth zone recovery.

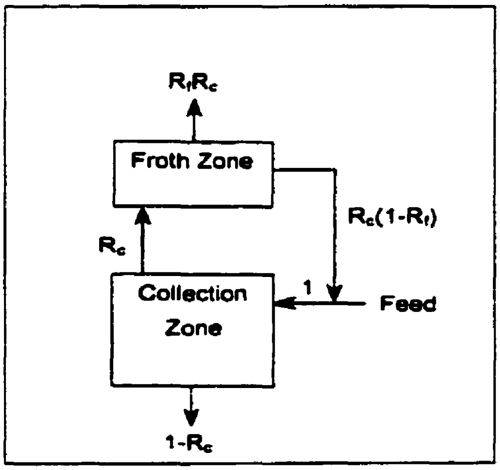


Figure 4.6 Conceptual interaction between collection and froth zone. (From Finch and Dobby, 1990).

The froth zone concentrate flow is given as R_cR_f and the drop back to the collection zone is given by $R_c(1-R_f)$. Overall flotation column recovery R_{fc} is then given by:

$$R_{fc} = \frac{R_f R_c}{R_f R_c + (1 - R_c)} \tag{4.28}$$

To calculate the recovery of a component, knowledge of three factors is required: the mixing regime, the retention time, and the collection zone rate constant. Using the laboratory scale column overall recovery and retention time data can be collected. Using equation 4.19 (collection zone recovery for a plug flow first order rate process) the overall collection rate constant can be determined. Overall rate constant can then be equated to collection zone rate constants assuming perfect froth zone recovery. This assumption is acceptable 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 (4.4.2). An important note is that the target recovery is an overall recovery for the system, while the recovery from the plug flow dispersion model is a collection zone recovery. Therefore, the target recovery must be converted to R_c using equation (4.28) after assuming a value for R_f (typically 0.5). Perfect froth zone recovery cannot be assumed for larger diameter columns due to significant amounts of froth dropback.

Scale-up is completed by specifying various parameters (viscosity, density, and particle diameter) and typical operating conditions (gas holdup, liquid flow rates) optimized in laboratory work and solving the equations for the plug flow dispersion model by iteration. Selectivity between various components can be determined by calculating the recoveries of the various components under the specified geometry.

4.6.2 Air Sparging System

4.6.2.1 Internal

The air sparging system used in a full-scale flotation column should provide the same surface area rate (S_b) as the laboratory column in order to achieve equivalent results. This can be achieved by keeping the bubble diameter and superficial air velocity constant. When using spargers that produce bubbles from the sparger surface, this scale-up requirement is achieved by maintaining the same R_s ratio as used in the laboratory tests (Xu and Finch, 1989). The R_s ratio is defined as:

$$R_s = \frac{Ac}{As} \tag{4.29}$$

where A_c is the cross sectional area of the flotation column and A_s is the sparger surface area. The bubble diameter for R_s values less than or equal to 1 can be predicted for porous spargers by the empirical equation that follows:

$$d_b = C_1 (R_s \cdot J_g)^n \tag{4.30}$$

where C_1 and n are constants. For porous spargers, n has been found to be about 0.25 (Dobby and Finch, 1986). C_1 depends on surfactant concentration, for example.

4.6.2.2 Microcel™

Experimental and theoretical studies carried out by Brake et al., (1996) have shown that a static mixer sparger can be scaled-up using the following equation:

$$d_b = C\left(\frac{D_h}{k}\right)\left(\frac{\varepsilon_{g}}{We}\right) \tag{4.31}$$

where d_b is the mean bubble diameter at the exit of the in-line mixer, D_h is the in-line mixer hydraulic diameter, ε_g the volumetric fraction of gas at the sparger inlet (high pressure side), *We* the dimensionless Weber number, *k* is the in-line mixer pressure drop constant, and *C* and *m* are scale-up constants. The *k* value for a given mixer depends on the number and configuration of mixing elements and can be experimentally determined from plots of pressure drop versus volumetric liquid flow rate. *We* is calculated using:

$$We = \frac{\rho \left(J_{l(s)} + J_{g(s)} \right)^2 L}{\sigma} \tag{4.32}$$

in which the $J_{g(s)}$ is the superficial gas rate to the in-line mixer, $J_{l(s)}$ the average slurry velocity in the mixer, ρ the slurry density, L the in-line mixer length, and σ is the surface tension of the slurry. According to equations (4.31) and (4.32), bubble size can be reduced by increasing the flow rate, mixer length and pressure-drop constant or by decreasing the slurry surface tension.

A second scale up factor to be considered is whether the in-line mixer can operate at the specified gas holdup ($\varepsilon_{g\,(s)}^{\bullet}$) at the sparger exit, which is defined as:

$$\varepsilon_{g(s)}^{\bullet} = \frac{J_{g(s)}}{J_{g(s)} + J_{l(s)}} \cdot 100 \tag{4.33}$$

Studies conducted using large scale in-line mixers indicate that the gas holdup exiting the sparger should not exceed 40 to 50 %. Thus, if the desired values of $J_{g(s)}$ and d_b are known, equations (4.31) and (4.32) can be used to calculate $J_{l(s)}$ for a given application. An appropriate pump can then be selected to provide the required $J_{l(s)}$.

4.7 ANALYTICAL TECHNIQUES

In the flotation deinking field, the comparison and evaluation of results from different processes and the formulation of firm conclusions are often difficult (Milanova and Dorris, 1993). This is due to a number of factors including: the inherent heterogeneity of waste paper; the wide variety of printing inks; and most importantly, the lack of standard methods for sheet making and measuring ink removal. This has had the effect of slowing down the development of new equipment and processes (and their acceptance by mills) (McKinney, 1988). The efficiency of the flotation process can be measured using a number of analytical techniques and is a function of pulp quality and process throughput. This section will describe two techniques to measure recycled pulp quality (Brightness and ERIC) and one technique to measure process throughput (Organic Loss).

4.7.1 Brightness

Brightness is the measurement of blue light reflected by paper at an effective wavelength of 457 nm and a bandwidth of 44 nm (Bristow, 1994). This measurement was originally developed to evaluate bleaching efficiency, and the 457 nm wavelength was chosen because the brightness increases between unbleached and bleached pulp reaches its maximum at this wavelength (Clark, 1985). Brightness is often used to measure the efficiency of flotation deinking systems but it has the major drawback that there is no direct correlation with the ink concentration. It has been demonstrated that small ink particles affect brightness to a greater extent than do larger ink particles (Zababla and McCool, 1988). There are other limitations as well, brightness is also affected by factors such as: fiber type and fines content; filler types and size distribution; colour; and the presence of optical brightening agents (McKinney, 1988). Brightness gain (B_{gain}) is measured in points and is the difference between the flotation feed brightness (B_{feed}) and flotation accept brightness ($B_{accepts}$).

$$B_{gain} = B_{accepts} - B_{feed} \tag{4.34}$$

In a flotation system for deinking newsprint, the brightness gain can be of the order of 10-15 points. On the other hand, in deinking of mixed office waste (MOW), the brightness will increase 5-10 points. Brightness measurements are included in this thesis because they are used by Bowater plant personnel to quantify the performance of the deinking circuit.

4.7.2 Ink Concentration

Brightness is sensitive to the presence of ink and other factors. This makes it an ambiguous index of the tinting power of the ink itself. It is this problem that has lead to a novel method called ERIC (Effective Residual Ink Concentration) developed by Jordan (Paprican) (Shen et al., 1997) to measure the amount of ink in a paper sample. It is based on the reflectance of light (R_∞) measured at a wavelength of 950 nm. This measurement is non-linearly related to the amount of ink in the paper but can be linearized by applying Kubelka-Munk theory and gives a concentration of ink in parts per million. For a more detailed explanation of the ERIC measurement please refer to the paper by Jordan and

Popson (1994). The ink concentration values can then be used to determine flotation efficiency (E):

$$E = \frac{c_i - c_f}{c_i} \times 100 \tag{4.35}$$

where c is the concentration of ink and the subscripts are for initial (i) and final (f). The ERIC numbers along with other measured values can also be used to calculate ink recovery (R). which is defined as:

$$R_{ink} = \frac{[c_i S_i Q_i \rho_i] - [c_f S_f Q_f \rho_f]}{[c_i S_i Q_i \rho_i]} \times 100 \tag{4.36}$$

where S is the consistency, Q is the volumetric flow rate and ρ is the density of the two streams.

4.7.3 Organic Loss

Organic loss (L) is another method for assessing the performance of a flotation device. Organic loss represents the amount of fiber which is lost in the reject stream. An overall material balance is required before organic loss can be determined. This material balance is a function of stream flow rates: feed (F), wash water (W), accepts (A), and rejects (R) and can be expressed as follows:

$$F + W = A + R \tag{4.37}$$

The main components of each stream are: water, organics and ash. Ink is a component of each stream, however it can be assumed that the mass is negligible (Watson, 1996). Organic loss is calculated according to the following equation:

$$L = \frac{R \rho_r X_r}{F \rho_f X_f} \tag{4.38}$$

where X is the mass fraction of organic material in reject (r) and feed (f) stream. Yield (Y) is the complement of organic loss and is used to determine process throughput of a flotation device. It is given by:

$$Y = 1 - L \tag{4.39}$$

⁂ CHAPTER FIVE ⁂

Experimental Methods

5.1 EXPERIMENTAL APPROACH

Deinking experiments were performed at Bowater's Gatineau mill using a laboratory scale flotation column. Two different air-sparging systems were tested on the column; an internal stainless steel porous sparger and an external static mixer system based on the Microcel™ concept. The column was fed continuously with the pulp bled from the feed line to the plant flotation circuit. Various operating conditions were altered in the columns depending on which sparging system was used. In the case of the internal sparger; gas rate, retention time, froth depth, column height and bias rate were altered. In the external sparger case the effects of gas rate, retention time, column height and sparger velocity were investigated. Deinking experiments with the different sparging systems were then compared using ink recovery and organic loss.

The results from the comparative studies were used to select the best operating conditions required for running each sparging system. Once the conditions were determined, long-term tests (7 hours) were run to compare both sparging systems in terms of ink recovery and organic loss. These tests were also used to probe long-term maintenance issues, gather scale up data and to make a further comparison to the plant flotation circuit. The obtained scale-up data was used in an exercise to design an column flotation circuit to treat the full Bowater capacity.

5.2 EXPERIMENTAL APPARATUS

5.2.1 Laboratory Scale Column

The laboratory-scale column used during the experimental program was constructed of clear acrylic plastic with an inner diameter of 10.1 cm and adjustable up to a height of 4.65 m. The column is portable and fully automated (Figure 5.1). Four pressure transmitters (Bailey, model PTSDDD122B2100) were installed along the length of the column in order to measure the gas holdup profile and to control the height of the slurry/froth interface. Three peristaltic pumps (Masterflex, model 7529-20), equipped with I/O cards, were used to control the flow of feed, accepts, and wash water.

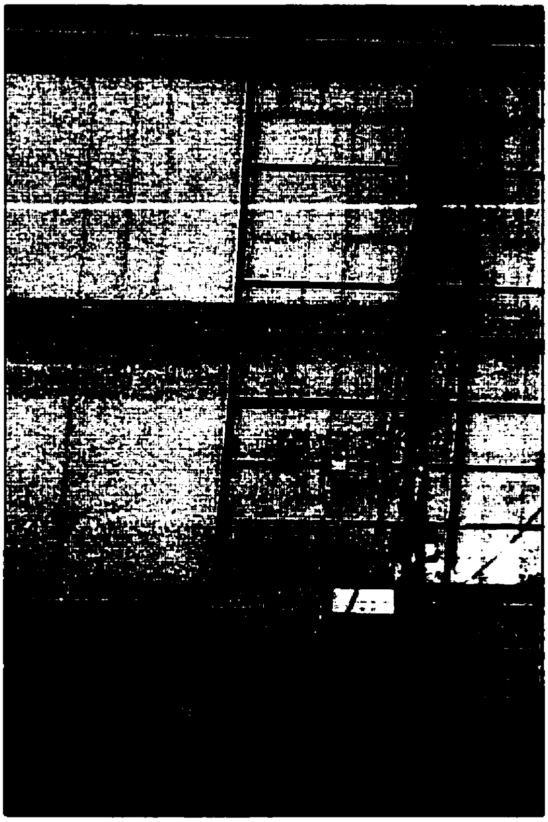


Figure 5.1 Laboratory flotation column setup (Picture: G. Leichtle).

The flow rate of feed and accepts stream was measured with magnetic flow meters (Fisher & Porter, model 10D1475PN07PL29). The rejects flow rate was measured using a 2-liter graduated cylinder and a stopwatch. The wash water distributor, made of a blocked pipe with many fine orifices at the bottom, was located about 4 cm above the top of the froth zone and wash water addition rate was controlled by a small Masterflex pump. The gas rate was controlled with the aid of a mass flow meter and controller (MKS, Model 116B-30000SV). Compressed air for the air flow meter was supplied at 80 psi from the plant and was reduced to 60 psi using a regulator. The pressure transmitters, pumps, and flow meters were controlled or monitored using a serial I/O (Transduction, model OPTO1) and a computer (IBM compatible, Pentium 200 MHz). The software used for data collection and control was FIX MMI 32-bit by Intellution. Other variables not routinely automated and measured were temperature and pH, using a portable pH meter (Yokohama) equipped with a temperature readout.

5.2.2 Internal Sparging System: Description

The internal sparger tested was a porous sintered stainless steel tube supplied by Mott Industrial and was installed horizontally in the base of the flotation column. A schematic of the column with the internal sparging system is shown in Figure 5.3 while a close up of the actual installation is shown in Figure 5.2. The stainless steel sparger was 10.5 cm long and 2.2 cm in diameter, which resulted in a surface area of 70 cm^2 (R_s= 1.14). The manufacturers claimed nominal pore size was 0.5 μm while lab measurements indicated an equivalent pore size of 2 μm (Escudero, 1998)

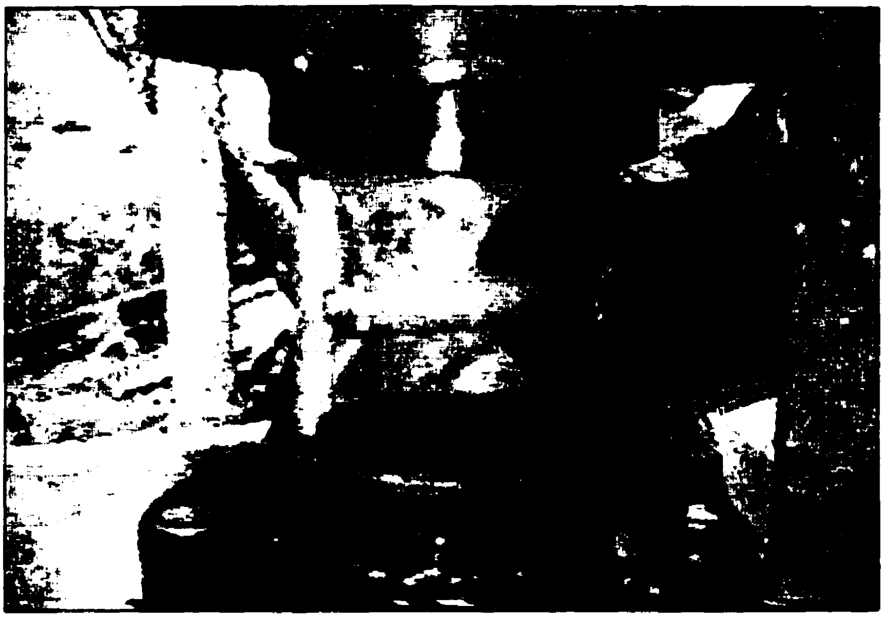


Figure 5.2 Porous internal sparger installed in bottom of laboratory flotation column (Photo: C. Hardie).

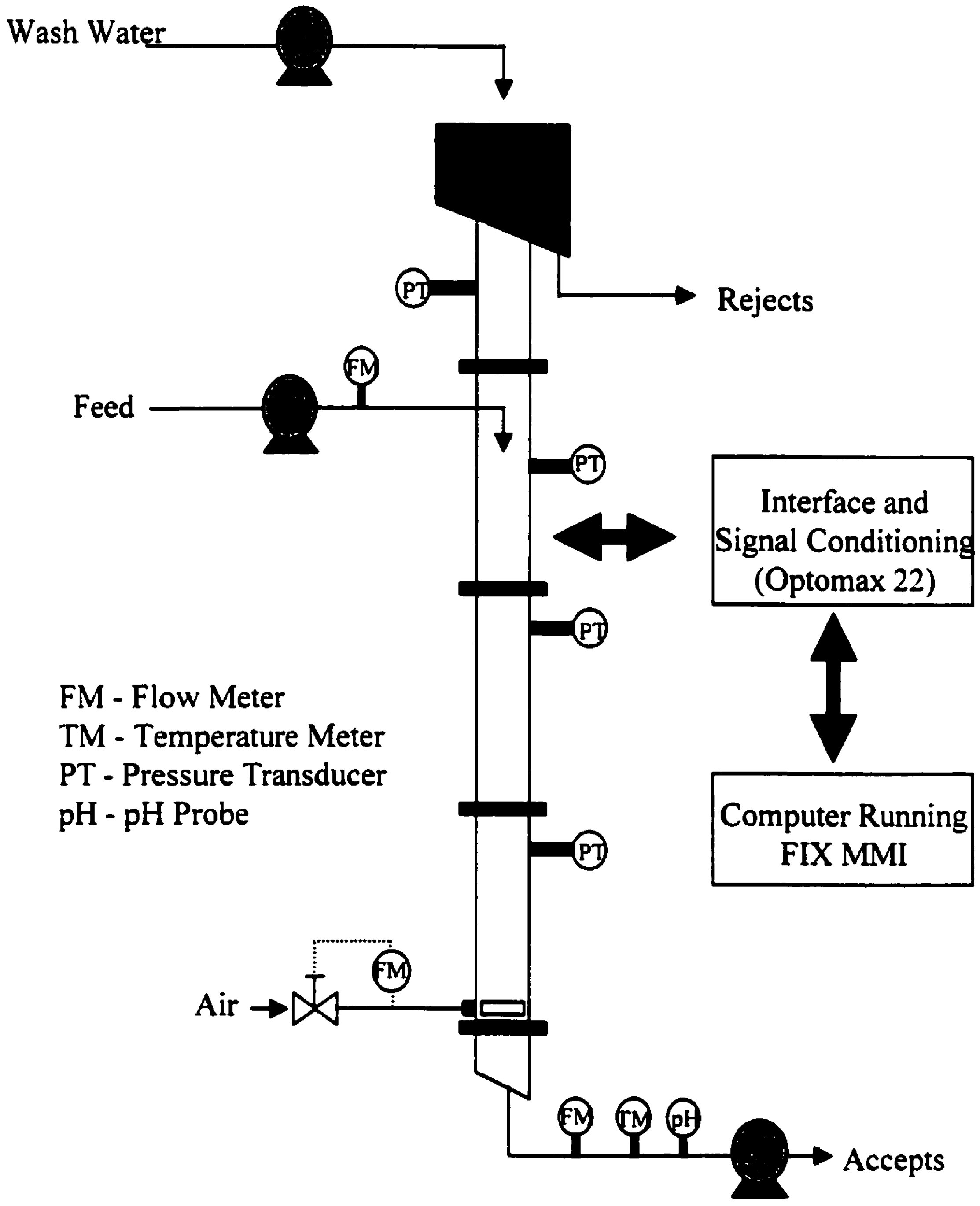


Figure 5.3 Schematic diagram of flotation column and internal sparging system.

5.2.3 External Sparging System: Description

The external static mixer system was designed according to specifications given by G. Luttrell (1997) (Virginia Polytechnical and State University) and assembled from readily available parts. A schematic of the column with the external sparging system is shown in Figure 5.5 while a close up of the system used during the test work program is shown in Figure 5.4. In this sparger system, slurry is withdrawn from the column by means of recycle loop and centrifugal pump (Gould, model 3642) and is passed through a 1 inch diameter static mixer (Koflo static mixer, series 308, 6 mixer elements and straightening vane). Air is introduced into the slurry just before it enters the static mixer and the slurry bubble suspension is re-introduced to the bottom of the column. The slurry flow rate is monitored by a flow meter (Krohne, model IFC 080) and is controlled using a gate valve. The static mixer velocity (S_{vel} in m/s) can be calculated from the sparger liquid flow rate (S_{flow} in l/min) by the following equation:

$$S_{vel} = 0.03 \cdot S_{flow} \tag{5.1}$$

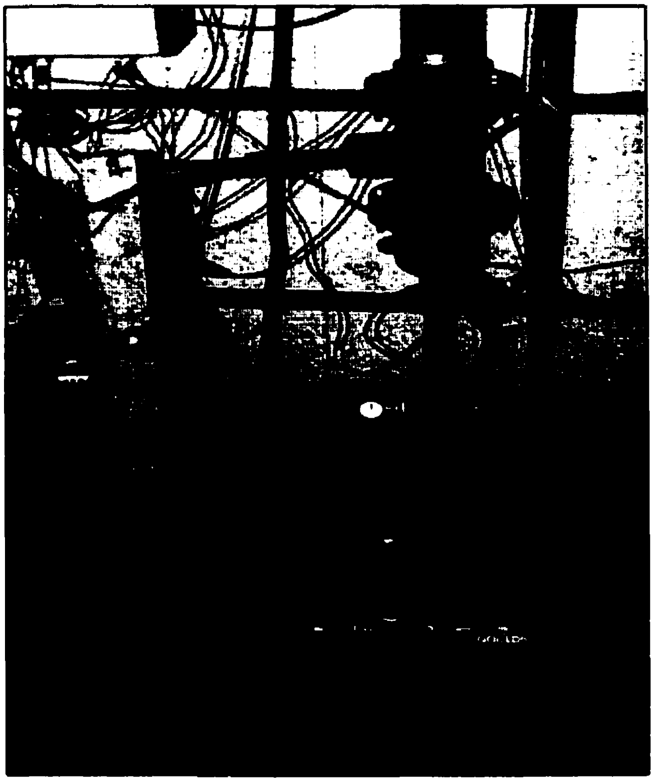


Figure 5.4 External static mixer air sparging system (Photo: C. Hardie).

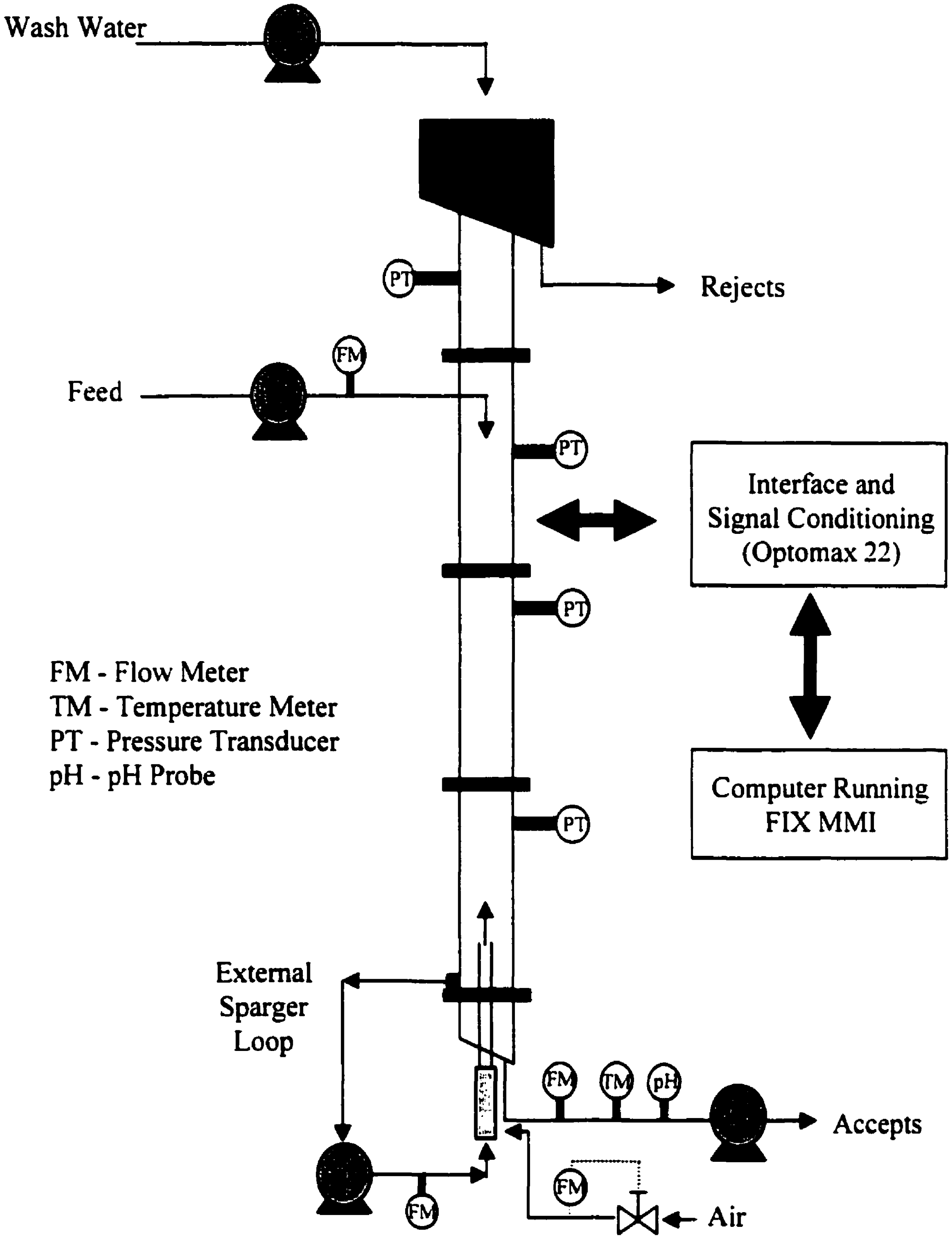


Figure 5.5 Schematic of the flotation column and the external sparging system.

5.3 EXPERIMENTAL PROCEDURES

5.3.1 Column Operation and Procedures

The experiments were divided into four different areas:

1) Testing of the sparging devices under batch conditions in two different systems: A) with water and 30 ppm Dowfroth B) flotation feed pulp.

2) Running a test with pulp to determine the relative standard deviation of various measured parameters.

3) Testing the sparging devices using pulp to determine the best operating conditions.

4) Running long term tests based upon selected operating conditions to determine scale-up parameters and sparger stability.

Work in the first and third area involved changing the sparging system between tests to minimize systematic errors and plant influences.

The level, pump flow rates, and gas rate were controlled using FIX MMI with the required parameters for each test being entered into the computer. The throughput of the column was fixed by setting the feed at a pre-determined flow rate. The accept flow rate was varied by the control program to maintain the froth height at the desired set point. The following parameters were collected continuously during each test: feed and accept flow rates, gas rate, gas holdup, and level. Reject flow rate was measured manually. Samples of the column feed, accept and reject streams were collected for analysis (consistency, brightness, ink concentration and ash content) after 1 hour and 1.5 hours of operation to get an average value. Feed and accept samples from the plant flotation circuit were also collected for analysis at the same time the other samples were collected. For the long-term tests the same basic procedure was followed except that samples were taken every hour.

5.3.2 Pad Preparation

In order to measure ink concentration and brightness for the feed and accepts stream, 4 gram pads were prepared using Bowater's pad preparation procedure. The 15 cm diameter pads were made using the following procedure:

1) Approximately 3/4 of liter sample was obtained from the appropriate stream.

2) The sample was mixed and then filtered through filter paper (Ahlstrom 617 grade, 15 cm diameter, very fast filtration speed) in a Buchner funnel. The volume of sample filtered was large enough to have a final dry pad weight of 4 grams.

3) The filter paper was removed and the sample was pressed between two blotter sheets using a mechanical press to remove excess moisture. The pad was then labeled with the test number and placed on a fan to dry.

5.3.3 Pad Analysis: Ink Concentration and Brightness

The feed and accept paper pads were analyzed for brightness and ERIC using a Technidyne ERIC 950 in the Paper Lab at Bowater's mill. Five scans on each side of the pad were done for brightness while 3 scans on each side were done for ERIC.

5.3.4 Solids Content

Measurement of solids content (consistency) of each stream was done for two reasons: 1) to ensure that tests were performed at similar consistencies as consistency is known to affect the flotation process; 2) to provide necessary information for mass balancing the column. To determine the consistency of each of the column streams, the following procedure was followed:

1) 250 ml of well-mixed sample was accurately measured using a graduated cylinder.

2) The sample was then poured into a Buchner funnel and filtered using pre-weighed Ahlstrom filter paper.

3) The pad and filter paper were removed and placed in an oven at approximately 150 °C until dry.

After drying, the pad and filter paper were weighed on a balance to obtain the dry sample weight.

The percent solids were then calculated according to the following formula:

$$Consistency(\%) = pad(g) \cdot \frac{\rho}{250} \cdot 100 \tag{5.2}$$

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

5.3.5 Ash and Fiber Content

To determine the column fiber losses, it is necessary to quantify the amount of ash and fiber content in each stream. At 575°C all organic constituents (primarily fibers) are combusted leaving inorganic ash material (Clay and $CaCO_3$). The ashing procedure, which closely follows TAPPI official standard T 211, was as follows:

1) Approximately 0.5 grams from the two test pads obtained for each stream was placed in ceramic crucibles, dried, and then weighed.

2) The crucibles were then placed in an oven at 575°C for 3 hours to burn all the carbon.

3) The crucibles were removed and weighed.

To determine ash content, the following equation was used:

$$Ash(\%) = \frac{A}{B} \cdot 100 \tag{5.3}$$

where A is the weight of the ash in grams and B is the moisture free weight of the test sample. This ashing technique is necessary to mass balance the column.

5.3.6 Column Mass Balancing

Mass balancing is necessary due to uncertainties (quantified by standard deviation) associated with experimental data. In this thesis, data reconciliation was performed using Norbal 3 (Spring, 1985) on all parameters except ink content whose mass was assumed to be negligible (Watson, 1996). Standard deviations for flow rates where taken from FIX MMI, while standard deviations of consistency and ash content were assumed using values obtained from statistical tests (see Section 6.4).

◊ CHAPTER SIX ◊

Results and Discussion

6.1 OVERVIEW

The following is a presentation and interpretation of the results and observations from the flotation column test program. This chapter is divided in 8 parts. To begin, a general characterization of the feed material is presented in Section 6.2. Section 6.3 is concerned with the batch testing of the porous and static mixer spargers in two flotation systems: water and surfactant; and pulp. In Section 6.4, a test was run to determine the relative standard deviations and 90 % confidence intervals of various measured values. Section 6.5 is concerned with the selection of operating conditions for the two sparging systems. Section 6.6 compares the results of the two sparging systems using both mineral processing and waste paper deinking techniques. Section 6.7 presents the results of long term testing with the selected operating conditions. Section 6.8 compares the results of this work to previous studies in the same area. Finally, Section 6.9 presents options proposed by two companies for a full-scale column circuit to treat the flow at Bowater's Gatineau mill based on the test scale-up parameters produced in this thesis.

Ink recovery, organic loss, and operational stability was used to analyze and compare the effects of various operating conditions. All flows are expressed as superficial rates (volumetric flow per unit column or static mixer cross sectional area) with units of cm/s or m/s. The pulp consistency (% solids) for all experiments was maintained at approximately 1.2 % by the plant. At no time were extra reagents added to the flotation plant feed. Batch test results are summarized in Appendix A. Operating conditions and results for the two sparging systems are summarized in Appendix B and C. Appendix D is reserved for the results of the long-term tests. Circuit survey results of the Bowater flotation circuit are in Appendix E while the results of the previous 1996 test work are in Appendix F.

6.2 CHARACTERIZATION OF FLOTATION PLANT FEED

In-plant trials carry the inherent problem of variations in feed composition, be it due to type of waste paper furnish, pulping conditions, reagents or combinations thereof. Ideally, one should know what is being fed to a flotation system in a complete description as possible and be aware of the fluctuations that may influence the results. Since a physical separation is only possible when distinct differences among the particles exist, the surface chemistry differences imparted by the collector / surfactant allow for selective flotation of ink particles. In mineral processing, which may also apply to waste paper deinking, it has been shown that only a small percentage of floatable material is required in a locked particle for flotation (Sutherland, 1989). Studies by Berg et al. (1996); Serres et al. (1993); and Sjöström and Calmell (1995) show that ink is not fully detached during repulping. Therefore, depending on the separation, some contamination of the reject stream with fiber and the accept stream with ink should be expected. Figure 6.1 is a plot of the feed ink concentration and consistency as a function of the test number.

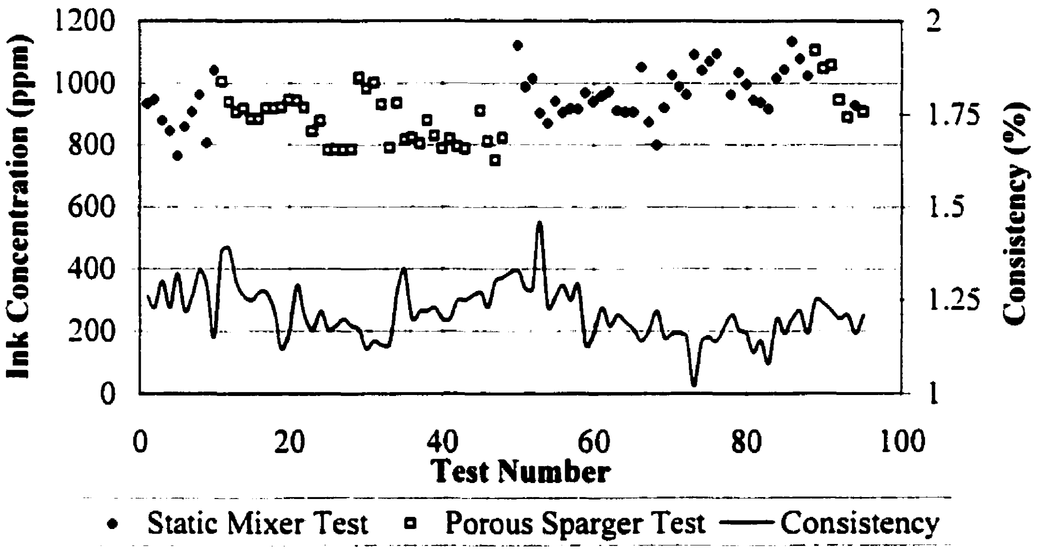


Figure 6.1 Feed ink concentration and consistency during test work.

As can be seen fluctuations in consistency and ink concentration occurred during the test program. A statistical analysis is presented in Table 6.1. Consistency during testing of both spargers remained fairly constant with an overall average of 1.22 % and a absolute standard deviation of 0.07 %. Banisi et al. (1995) in a study on column flotation found that the presence of solids (i.e. increased slurry consistency) caused a decrease in gas holdup. They attributed this to an increase in bubble swarm velocity due to wake stabilization caused by the presence of solids increasing slurry viscosity. Janse et al. (1997) also found that as consistency rose gas holdups were lower. Pulp consistency can be expected, therefore, to affect the collection of ink particles.

The feed ink concentration for the static mixer tests was slightly higher (approximately 72 ppm) than for the porous sparger tests. This indicates that if comparisons of pulp quality for flotation tests are made using absolute values such as the accepts ERIC, without accounting for feed values, the variation in feed ink concentration may influence the outcome. This is not considered a problem, however, as the ink recovery calculation (Equation 4.3.6) used is a relative measure of deinking performance.

Table 6.1 Feed ink concentration and consistency statistics over the test program. Variance (+/-) is given as a 90 % confidence interval.

Test	Feed Ink Concentration (ppm)				Feed Consistency (%)			
	Mean	+/-	Std Dev.	Rel. S.D	Mean	+/-	Std Dev.	Rel. S.D.
Static Mixer	960.7	19.9	83.0	8.6	1.21	0.02	0.09	7.4
Porous Sparger	889.1	22.1	86.4	9.7	1.23	0.02	0.06	4.9
Overall	**927.2**	**15.8**	**91.5**	**9.9**	**1.22**	**0.01**	**0.07**	**5.7**

Little was known about reagent dosages or other operating conditions such as plant feed flow rate during the campaign. The reagents added to the pulper and flotation circuit according to Bowater personnel were sodium hydroxide, fatty acid soap, hydrogen peroxide, calcium chloride and sodium silicate (Bowater,1998).

6.3 BATCH TEST RESULTS

One method of characterizing sparging systems is to determine the relationship between gas holdup and superficial gas rate (Xu and Finch, 1989). The two sparging devices were first tested under batch conditions using water (22°C) and 30 ppm Dowfroth 250C and then with 1.3 % consistency pulp. These experiments were intended to indicate the relative performance between the two sparging systems and therefore the performance that could be expected during continuous testing with pulp. The tests performed in the laboratory column were done using superficial gas velocities selected so that overflow did not occur. Superficial gas rates were corrected for pressure to midway between the pressure transducers (P2: 284 cm from top and P3: 375 cm from top). Figure 6.2 shows the relationship between the superficial gas rate (corrected for pressure) and gas holdup in a water/frother system for the porous 0.5 μm sparger (solid line) and static mixer sparger operated at varying superficial sparger liquid rates (Both spargers are described in Sections 5.2.2 and 5.2.3). The static mixer sparger superficial liquid rate (m/s) is calculated by dividing the volumetric liquid flow rate by the inside cross sectional area.

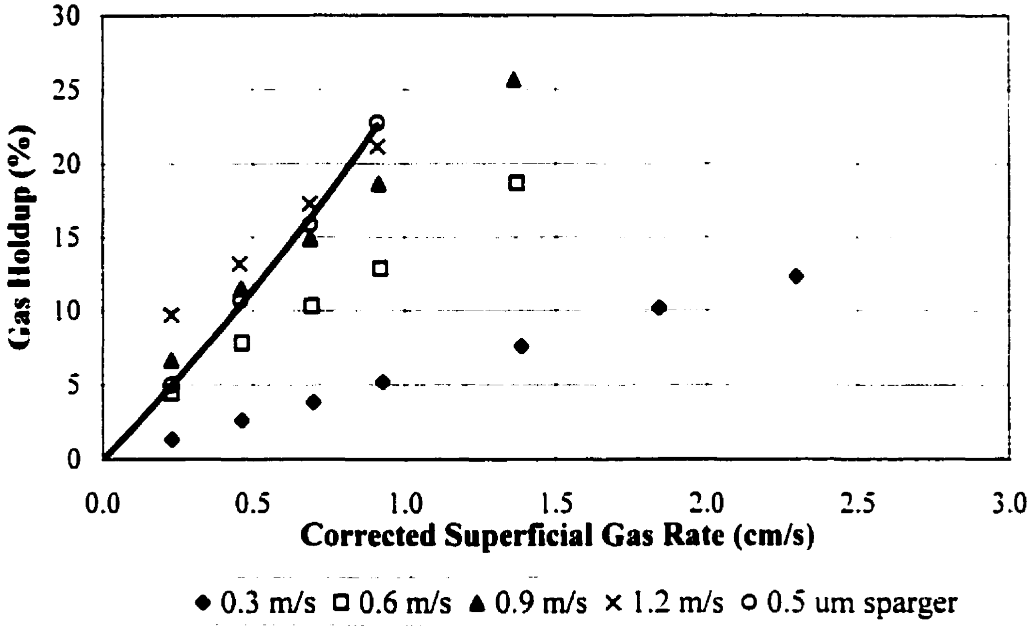


Figure 6.2 Gas holdup as a function of superficial gas rate for spargers in batch conditions using water and 30 ppm Dowfroth 250C. Conditions: see Appendix A.

Each point is the average of approximately 300 sample values collected over 5 minutes by the data acquisition system at the preset condition. The results indicate that as the liquid rate through the sparger is increased, gas holdup increases at an equivalent superficial gas rate. Gas holdup can be used as a sensitive indicator of change in bubble diameter (Xu and Finch, 1989). In this case, as the sparger liquid rate was increased, the higher gas holdup indicates that smaller bubbles are produced. At a sparger superficial liquid rates of 0.9 m/s and higher, the static mixer sparger achieved results comparable to the porous sparger.

Figure 6.3 shows the relationship between superficial gas rate (corrected for pressure) and gas holdup in pulp for the porous 0.5 μm porous sparger (solid line) and static mixer sparger operated at varying velocities. The static mixer gave similar results to the water/surfactant curve but the porous sparger gave much lower gas holdups. The gas holdup/gas rate relationship between the internal and external sparger seems to have changed. For example, the porous sparger at a superficial gas rate of 0.75 cm/s produced a gas holdup of approximately 16 % in the water/frother system but in the pulp system the gas holdup was only 7 %.

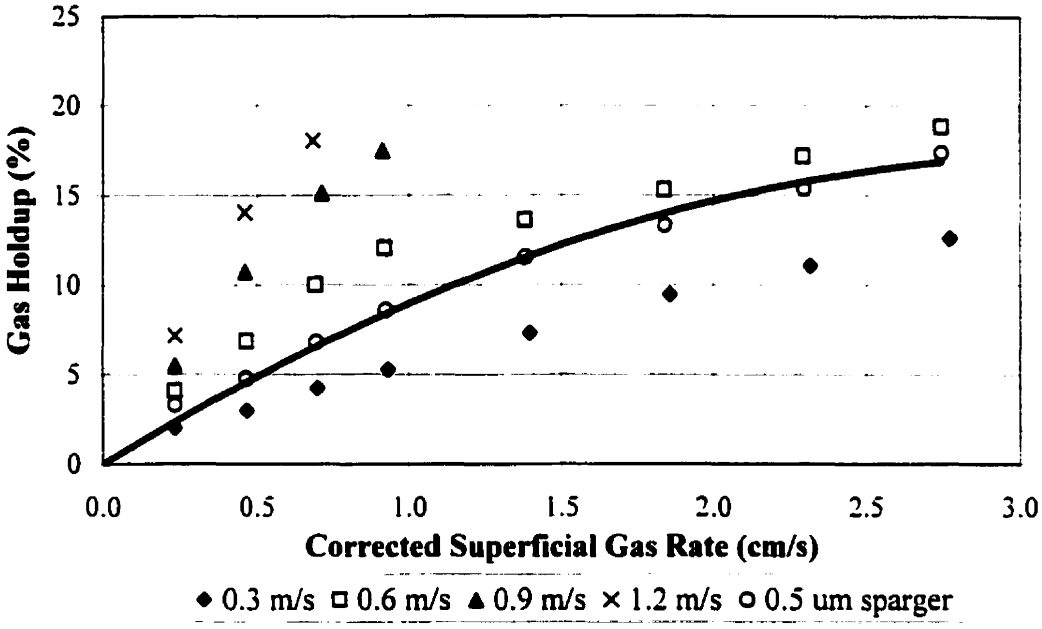


Figure 6.3 Gas holdup as a function of gas velocity for spargers in batch conditions using pulp (1.3% consistency). Conditions: See Appendix A.

Visual observations and calculations using the drift flux model (Appendix A) indicated that the static mixer system was producing smaller bubbles than the porous sparger in the pulp system. The static mixer may keep the pulp fibers well dispersed, whereas in the porous sparger case, little movement of the pulp occurs and flocculation can easily result. If flocculation occurs, small bubbles may have to coalesce in order to have sufficient buoyancy to rise. These large bubbles would result in lower gas holdups than in a well dispersed system that allows most bubble sizes to rise. In the end, testing spargers in a batch pulp system may result in data that is not useful for predicting continuous system effects or for comparing sparging systems. If the effect of the sparger on slurry rheology cannot be carefully controlled between tests it may be more useful to base conclusions on the water/surfactant system where flocculation is not an issue.

6.4 STATISTICAL ANALYSIS / EXPERIMENTAL ERROR

In previous attempts to quantify the ability of column flotation technology to recover ink, little has been done to indicate the reproducibility of the experiments and various measurements. In an attempt to quantify experimental error without incurring a large increase in the number of tests, a simple test was run to gather basic standard deviation data that could be used for test comparisons. The standard deviation data were also important because they are required by Norbal 3.0, the material balance software used for mass balancing.

The flotation column was run at predetermined conditions: retention time, 4 minutes; gas rate, 2 cm/s; froth depth, 65 cm; bias rate, 0.13 cm/s with the internal porous sparger. After three residence times (15 minutes) of operation, the column was sampled 4 times over a 10 minute period. The experimental results along with a basic statistical analysis are shown in the following two tables. Table 6.2 shows the data provided by the data acquisition system (FIX MMI) while Table 6.3 shows the data obtained by direct measurement of each stream.

For the most part, the results of this test indicate that the operation and sampling of the flotation column is consistent. This is shown by low relative standard deviations (less than 3 %) of the various measured stream parameters. The reject stream gave the highest standard deviation, particularly in the flow rate and consistency measurements, which had relative standard deviations of approximately 10 %.

Table 6.2 Collected data from FIX MMI data acquisition software. Variation (+/-) given as a 90 % confidence interval.

Measured Parameter (units)	No. of values	Mean value	+/-	Std Deviation (unit)	Rel. Std Dev. (%)
Feed Rate (l/min)	201	4.14	0.01	0.07	1.69
Accept Rate (l/min)	201	4.76	0.03	0.23	4.83
Reject Rate (l/min)	4	0.11	0.01	0.01	9.09
Wash Water Rate (l/min)	10	.81	0.01	0.01	1.23
Air Rate (l/min)	201	9.72	0.00	0.002	0.02
Gas Holdup (%)	201	14.6	0.05	0.36	2.47

Table 6.3 Laboratory measured data. Variation (+/-) given as a 90 % confidence interval.

Measured Parameter (units)	No. of values	Mean Value	+/-	Std Deviation (unit)	Rel. Std Dev. (%)
Feed Consistency (%)	4	1.25	0.02	0.02	1.60
Accept Consistency (%)	4	1.08	0.01	0.01	0.93
Reject Consistency (%)	4	2.13	0.3	0.25	11.7
Feed Fiber Content (%)	4	87.29	0.42	0.36	0.41
Accept Fiber Content (%)	4	89.33	0.38	0.32	0.36
Reject Fiber Content (%)	4	55.82	2.6	2.21	3.96
Ink Recovery* (%)	4	71.5	1.79	1.52	2.12
Organic Loss* (%)	4	2.9	0.69	0.59	20.3

* These values are calculated after mass balancing

The large standard deviations of the rejects stream seems to be caused by two factors: column pulsation and froth zone phenomena. Depending on the column flow regime and pulp characteristics, the interface level is disturbed by the intermittent release of closely packed small bubbles. Baxter and Wraith (1970) may have also observed this phenomenon. This results in froth depth moving up and down slightly and thus deviations in overflow measurements. The second reason is a more qualitative than the first. It seems that a certain amount of material is required in the froth zone before it overflows. This gives rise to a build up and overflow action which results in intermittent discharge of material and thus deviations in measurements.

For the mass balanced values, the ink recovery has a 90 % confidence interval ± 1.7 % while the organic loss has a 90 % confidence interval of approximately ± 0.7 %. The confidence intervals, which show the reliability of each measurement, are included on the graphs in the following section.

6.5 SELECTION OF OPERATING PARAMETERS

To determine the optimum operating conditions for each sparging system and to compare with previous research a number of parameters were altered depending on the sparging system used. Testing the internal porous sparger involved changing the gas rate, pulp retention time, bias rate, froth depth and column height. The effect of gas rate, retention time, sparger velocity and column height were investigated using the external static mixer sparging system. Froth height and bias rate (provided > 0 cm/s) usually do not effect column performance to a great degree (Watson, 1996; Finch and Dobby, 1990) therefore only the porous sparger was used in testing these parameters. The selected operating conditions represent a compromise between ink recovery, organic loss, and operational stability.

6.5.1 Internal Porous Sparger

The internal sparger used in this test work is described in Section 5.2. The following sections (6.5.1.1 to 6.5.1.5) describe the effects of the various manipulated parameters on the internal porous sparger system. Variation in the experimental data is given as a 90 % confidence interval. All experimental conditions and material balances are in Appendix B.

6.5.1.1 The Effect of Pulp Retention Time

To calculate retention time, the volume of the collection zone corrected for froth depth and gas holdup was divided by the accept flow rate. The effect of retention time was investigated by varying the accept flow rate while holding all other operating variables constant. The effect of retention time on ink recovery and organic loss is shown in Figure 6.4.

Ink recovery increased rapidly in the first 3 minutes and slowed thereafter to a maximum value at about 12 minutes. The ink recovery plateau of approximately 82 % probably characterizes the maximum achievable ink recovery. Additional retention time will not remove any more ink because it is either still bound to fibers or too small to be effectively captured by the size of bubbles generated.

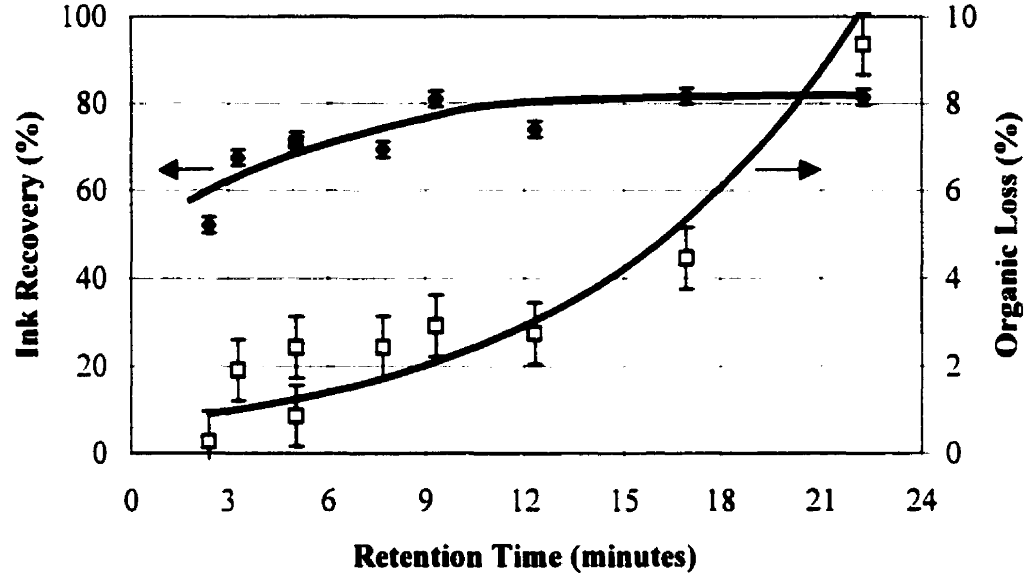


Figure 6.4 Ink recovery and organic loss versus slurry retention time. Conditions: gas rate = 1.5 cm/s; froth depth = 65 cm; column height = 4.65 m; bias rate = 0.12 cm/s.

Organic losses increased almost exponentially with pulp retention time. Therefore, long retention times should be avoided. The selected retention time for the porous internal sparger was 6 minutes, which corresponds to a pulp flow rate of approximately 3 l/min. Previous studies by Watson et al. (1996) using two different porosity spargers (0.5 μm and 100 μm) in the same size column showed similar results.

They found when using the fine porous sparger at a gas rate of 1.5 cm/s, ink recovery was essentially the same over a range of retention times (3 to 10 minutes) and organic loss increased.

6.5.1.2 The Effect of Gas Rate

The effect of superficial gas rate (J_g) on ink recovery and organic loss is shown in Figure 6.5. In order to isolate the effect of gas rate, the retention time, froth depth, and wash water rate were maintained at constant values. Gas rates (0 °C, 1 atm) were not corrected for temperature or pressure as comparisons with previous work would be difficult.

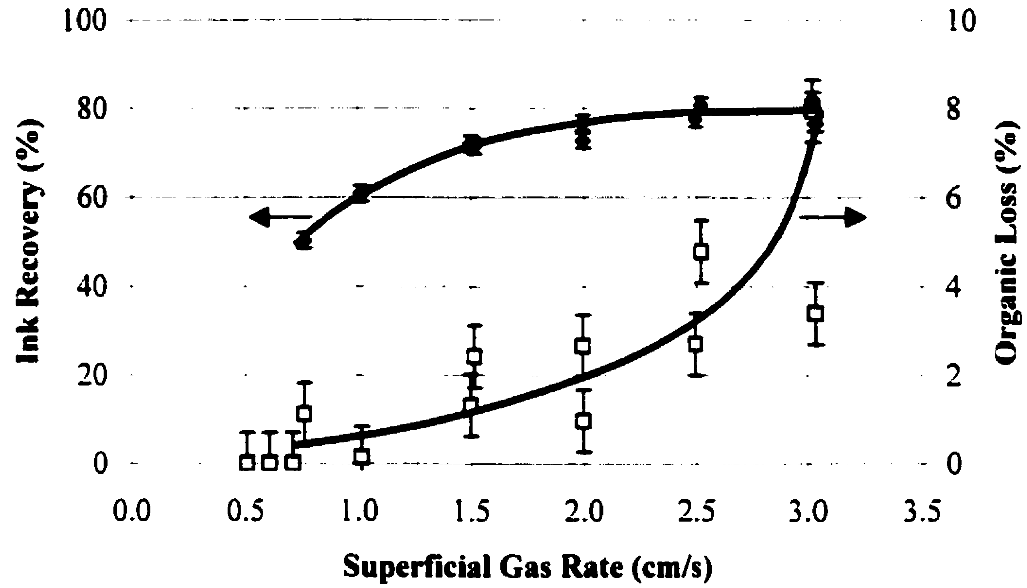


Figure 6.5 Ink recovery and organic loss versus superficial gas rate. Conditions: retention time = 5 minutes; froth depth = 65 cm; column height = 4.65 m; bias rate = 0.13 cm/s.

Ink recovery increased as the gas rate increased until a plateau of approximately 80 % was reached at superficial gas rate of 2.5 cm/s. At higher gas rates, the flow regime in the collection zone visibly changed from bubbly to churn-turbulent. Large bubbles rising quickly, back-mixing, and difficult level control characterized this change. Organic losses grew exponentially to 8 % as the gas rate was increased to 3.0 cm/s. The selected gas velocity was 2.5 cm/s. This value was chosen to give a compromise between good ink recoveries (78 %) and reasonable fiber losses (4 %).

Petri (1994) did similar ONP/OMG deinking studies using column flotation. He found that as the gas rate was varied from 0.5 cm/s to 2.5 cm/s, the ink recovery increased and plateaued between 1 and 2 cm/s. Data were not shown for organic losses nor was the type of sparger described. Watson et al. (1996) varied the gas rate between 1 and 4 cm/s for 0.5 μm and 100 μm spargers. They found for both that organic losses increased with air rate and ink recovery remained constant for the 0.5 μm sparger but increased for the 100 μm sparger.

6.5.1.3 The Effect of Bias Rate

The effect of bias rate was investigated by varying the wash water rate and keeping all over variables constant. Level was controlled by varying the accept flow rate. Figure 6.6 shows the effect of bias rate changes on ink recovery and organic loss. Positive bias water (net flow downwards) is known to reduce recovery of entrained particles.

In this case, bias rate had little effect on ink recovery and a large effect on organic loss. It was also found that producing a deep froth (greater than 50 cm) without wash water was difficult. Ink recovery remained constant at approximately 68 % when the bias rate was changed from -0.02 to 0.25 cm/s. Organic losses decreased from approximately 3.5 % at a slightly negative bias too less than 1 % at the highest bias rate of 0.25 cm/s. The selected bias value for future tests with both the internal porous and external static mixer sparger was 0.1 cm/s as it produced fairly low fiber losses. High bias rates are to be avoided, even if low organic losses are achieved, as they reduce the pulp retention time and dilute the accepts.

Previous work by Watson et al., (1996) showed that as the bias rate was varied, ink recovery and organic losses remained essentially the same. They found, however, that the visual character of the fiber pads was different. Low wash water rates (low bias rates) seemed to produce "hairy" pads which are probably a result of long fibers reporting to the reject stream through increased entrainment. High bias rates did not show this characteristic. This difference in pad "hairiness" was also seen in this work.

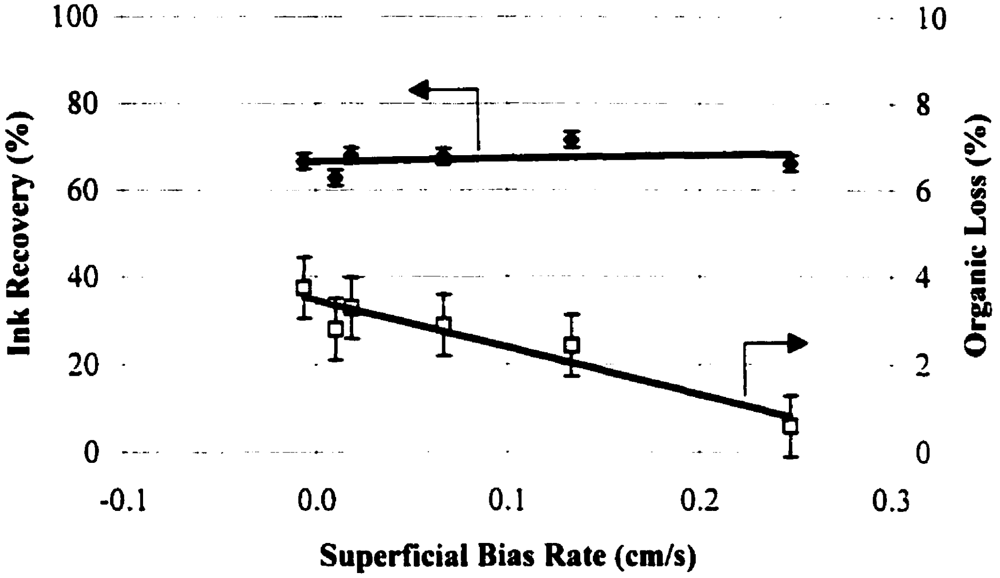


Figure 6.6 Ink recovery and organic loss versus superficial bias rate. Conditions: gas rate = 1.5 cm/s; retention time = 5 minutes; froth height = 65 cm; column height = 4.65 m.

Petri (1994) found that wash water had a negligible effect on ink recovery and actually increased organic losses. This increase in organic loss is opposite to what one expects. Increased mixing by adding more wash water in the froth zone may have caused this increase in fiber loss due to short circuiting of material from the collection zone to the column reject stream.

6.5.1.4 The Effect of Froth Depth

The effect of froth depth on ink recovery and organic loss for the internal porous sparger is shown in Figure 6.7. An increased froth depth provides more cleaning action, usually resulting in a cleaner rejects stream (i.e. less fiber loss in a deinking system). Ink recovery was not affected by froth depth, as it remained linear at a value of about 75 % throughout all depths tested. Organic loss, on the other hand, decreased from approximately 4 % at a froth depth of 10 cm to 2.4 % at a froth depth of 120 cm. The selected froth depth for both the internal porous and external static mixer sparger was 65 cm.

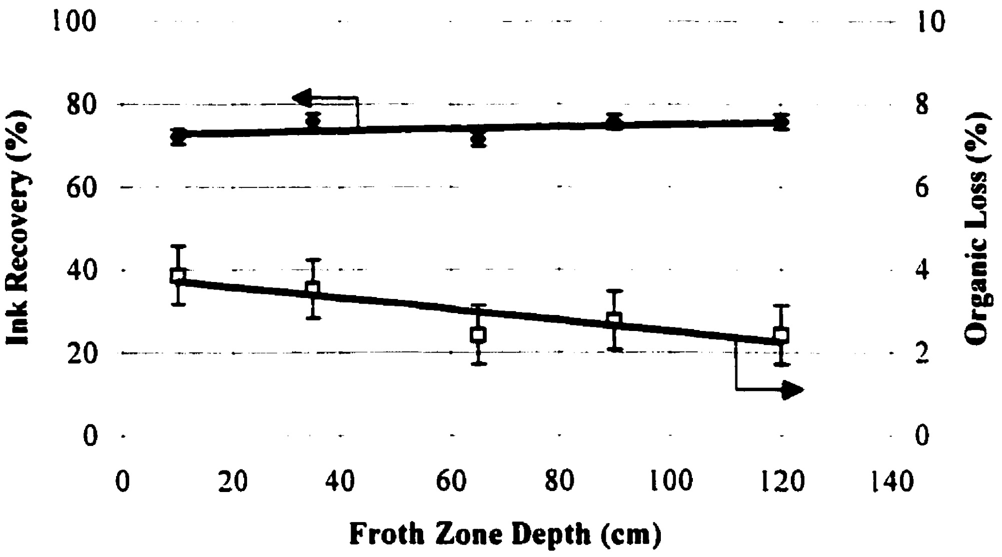


Figure 6.7 Ink recovery and organic loss versus froth zone depth. Conditions: gas rate = 1.5 cm/s; retention time = 5 minutes; column height = 4.65 m; bias rate = 0.12 cm/s.

Carabin et al., (1997) found that the reject rate (proportional to organic loss) decreased as froth height was increased. They choose a 30 to 40 cm froth depth in a 6-m tall column to avoid instability problems and fluctuations. Petri (1994) varied froth height from 10 cm to 45 cm and found that ink recovery decreased as froth height increased while organic losses remained constant. Watson et al., (1996) varied the froth height from 20 cm to 75 cm and found that both ink recovery and organic loss remained constant. Extremes in froth depth are not favorable to the operation of flotation columns. Shallow froths mean that the froth (cleaning) zone of the column is lost when surges occur; and deep froths decrease the working collection zone and thus reduce pulp retention time.

6.5.1.5 The Effect of Column Height

A literature survey indicates that almost nothing has been done to investigate the effect of column height in deinking waste paper. This is to be expected as column flotation deinking is still relatively new. In the minerals industry, however, there has been much debate as to how tall a flotation column should be. In most instances the selection of column height has been dictated not by the particle-collection process, but by physical restraints such as location of the mill roof or crane rails. Several studies

(Ounpuu and Tremblay, 1991, Bensley et al., 1985, and Ityokumbul, 1996)) have showed that increasing the height does not necessarily result in increased recoveries. Particle size may be the critical factor; as smaller particles have a reduced probability of collision with a bubble and tall columns may then be an advantage (Zhou et al., 1995). Microcel flotation column studies have shown this effect in that taller columns are required to process clay (<2 μm) particles than larger coal particles (Yoon, 1998). The effect of flotation column height on ink recovery and organic loss is shown for the present work in Figure 6.8 and Figure 6.9 respectively.

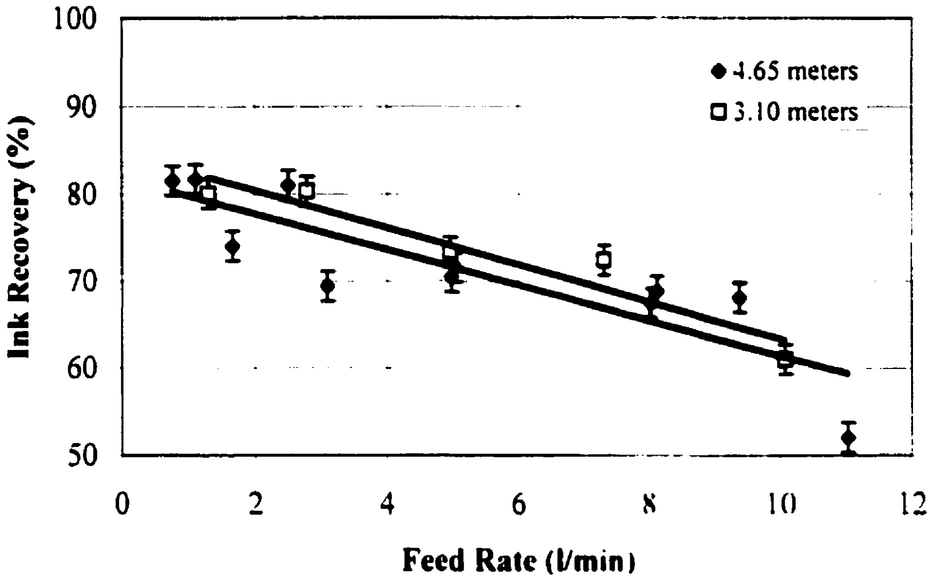


Figure 6.8 Ink recovery versus feed rate at two column heights. Conditions: gas rate = 1.5 cm/s; froth depth = 65 cm; bias rate = 0.12 cm/s.

Two heights of column were investigated: 4.65m and 3.1 m. All other variables were kept constant except feed rate. Column height had little effect on ink recovery with the 3.1 m column giving statistically similar ink recoveries to the 4.65 m column collection zone. This may indicate that the ink collecting process occurs very quickly in the column. In terms of organic losses however, column height seems to have a larger effect. At equivalent feed rates, the 3.1 m column gave consistently higher organic losses than the 4.65 m column. A clear explanation for this result could not be found. Factors such as furnish type and pulp chemistry may have also changed as the tests were done a number of weeks apart. The selected column height for future work with this system was, nevertheless, 3.1 m.

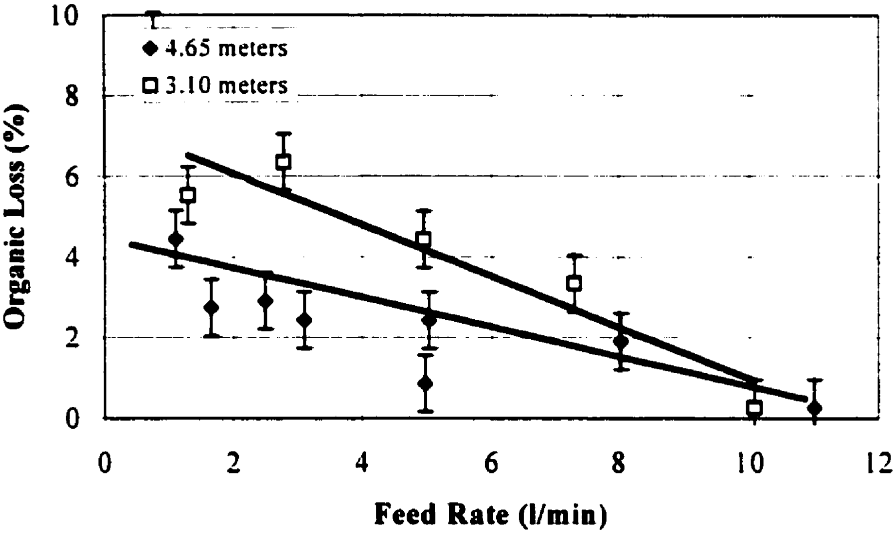


Figure 6.9 Organic loss versus feed rate at two column heights. Conditions: see Figure 6.8.

6.5.2 External Static Mixer Sparger

The external sparger used in this test work is described in Section 5.3. The following sections (6.5.2.1 to 6.5.1.4) describe the effects of the manipulated variables tested including: retention time, gas rate, sparger superficial pulp rate and column height. Froth depth and bias rate were not tested with the static mixer sparger because they were initially selected just to test whether previous results with porous spargers could be replicated. Based on those results, the same values were chosen for the static mixer sparger. Since this is probably the first time a deinking system based on a static mixer sparger has been tested there is almost no data which can be compared to the results here. Therefore, results from similar devices tested in mineral processing systems in some cases will be used to compare trends. A table showing the final selected operating conditions is shown in Section 6.7. All experimental data and material balances are in Appendix C.

6.5.2.1 The Effect of Pulp Retention Time

The effect of retention time on ink recovery and organic loss was determined by setting the gas rate, froth depth, and wash water rate at selected values. Retention time was changed from 2.2 minutes to over 10 minutes by varying the accept flow rate. This results in lower downward pulp velocities through the column, higher probability of particle/bubble contact and thus higher collection efficiencies. The effect of retention time on ink recovery and organic loss at two sparger pulp rates (i.e., the linear velocity through the sparger) is shown in Figure 6.10 and Figure 6.11, respectively.

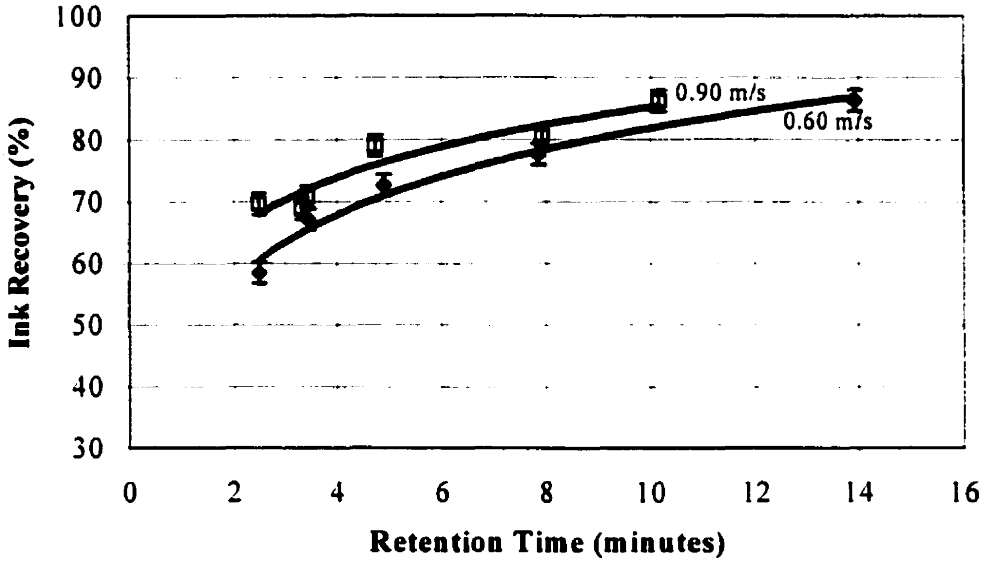


Figure 6.10 Ink recovery versus retention time at two sparger superficial pulp rates. Conditions: gas rate = 1.5 cm/s, froth depth = 65 cm; column height = 4.65 m; bias rate = 0.18 cm/s.

Two sparger pulp rates were tested to see whether a similar relationship was obtained. The sparger superficial pulp rate (m/s) is calculated by dividing the volumetric pulp flow rate by the cross sectional area of the static mixer and will be discussed more thoroughly in Section 6.5.2.3. Ink recovery and organic loss increased as retention time was increased for both sparger pulp rates. During these tests a plateau in ink recovery was not reached unlike the case with the porous sparger. Extrapolating the curve indicates that an ink recovery of approximately 88 % might be achievable at sufficient retention time. The difference in maximum ink recoveries is probably due to different pulping conditions during the experimental program and not a result of the type of sparger used. These results also indicate that by increasing the sparger pulp flow rate a statistically significant increase in ink recovery can be achieved.

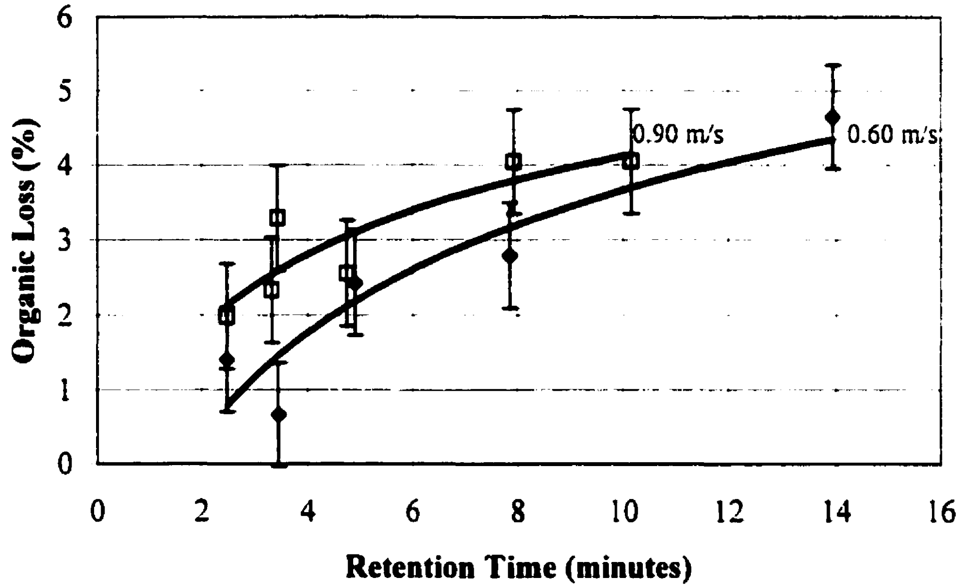


Figure 6.11 Organic loss versus retention time and two sparger superficial slurry rates. Conditions: See Figure 6.10.

Increasing the retention time from 2.2 minutes to over 10 minutes caused the organic loss to increase from about 1 % to over 4 %. This was expected from the previous work with the porous sparger which showed the same trend. To minimize organic loss and still obtain good ink recovery a pulp retention time of 5 minutes was chosen.

6.5.2.2 The Effect of Gas Rate

The superficial gas rate determines the bubble surface area rate and thus the ink carrying rate of the system. The effect of superficial gas rate on ink recovery and organic loss at 4 different sparger superficial pulp rates is shown in Figure 6.12 and Figure 6.13, respectively.

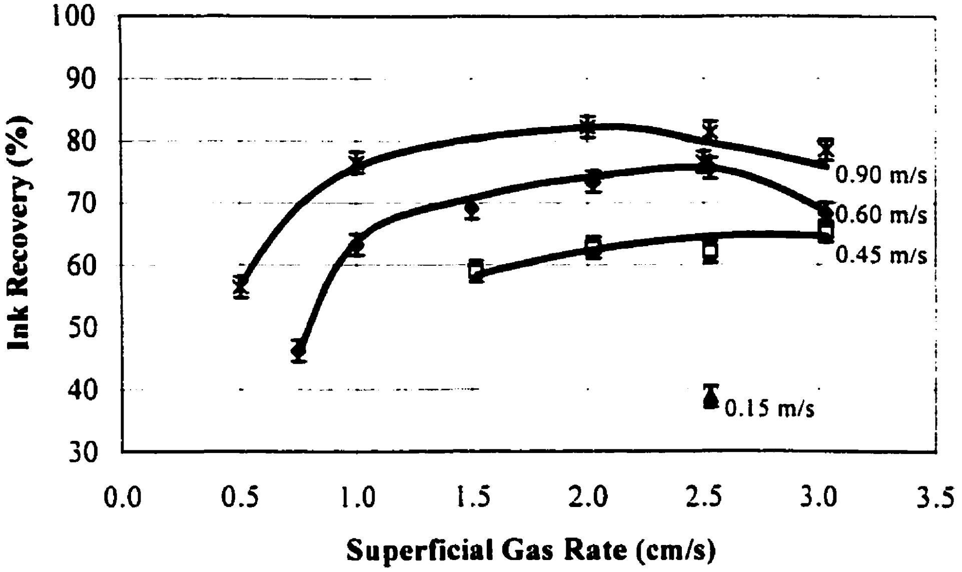


Figure 6.12 Ink recovery versus superficial gas rate at four sparger superficial pulp rates. Conditions: retention time = 5 min; froth depth = 65 cm; column height = 4.65 m; bias rate = 0.15 cm/s.

Ink recovery increased with gas rate, reaching a plateau between 1.5 and 2 cm/s depending on the sparger superficial pulp rate used. At a higher sparger pulp rate the ink recovery plateau increased. The maximum ink recovery, 83 %, occurred at a superficial gas rate of 2.0 cm/s and a sparger pulp rate of 0.9 m/s. Higher sparger pulp rates also allowed the column to be operated at lower gas rates. A gas rate of only 1.0 cm/s at the highest sparger pulp rate of 0.9 m/s was sufficient for column overflow and to give a ca 80 % ink recovery. The effect of sparger pulp rate will be discussed in more detail in the following section. As expected, organic losses became larger with increased superficial gas rates. Organic loss climbed from less than 1 % at a gas rate of 0.5 cm/s to over 5 % at a gas rate of 3.0 cm/s for the sparger pulp rate of 0.9 m/s. For the other sparger pulp rates the same trend was followed. The selected gas rate for the static mixer sparger was set at 2.5 cm/s as this gave the maximum ink recovery over the range of sparger pulp rates tested and keeps organic losses to a reasonable amount, about 3 %.

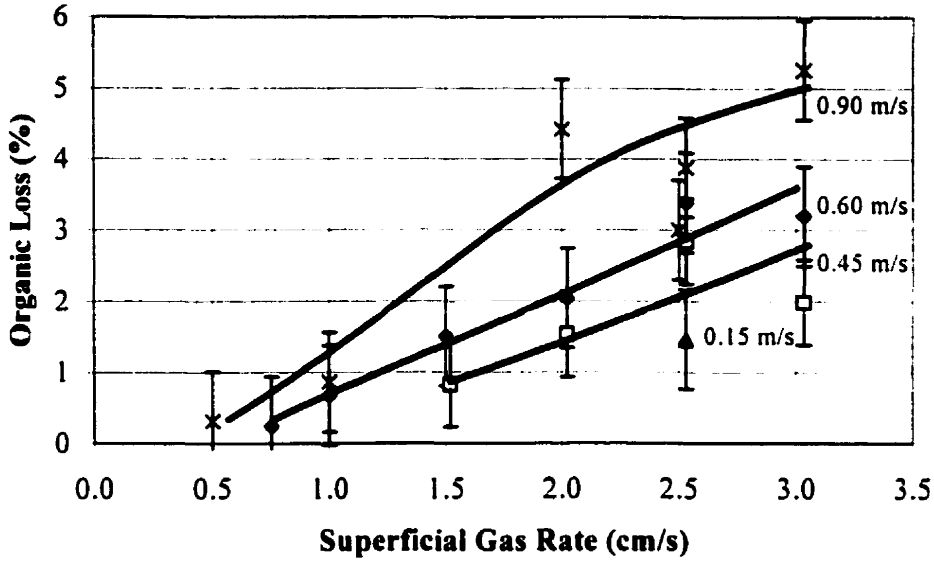


Figure 6.13 Organic loss versus superficial gas rate at four sparger superficial pulp rates. Conditions: see Figure 6.12.

6.5.2.3 The Effect of Sparger Superficial Pulp Rate

The effect of sparger superficial pulp rate was investigated using two gas rates, 1.5 cm/s and 2.5 cm/s. The effect on ink recovery (Figure 6.14), organic loss (Figure 6.15) and bubble size/surface area rate (Figure 6.16) was determined by setting the retention time, froth depth and bias rate at selected values. A feature of this system is the ability to control bubble size to some degree during column operation. This may be beneficial when variations in feed particle size occur due to changes in pulping conditions and a different bubble size may be desirable.

The first step in determining the effect of sparger pulp rate was to find the minimum and maximum limits to column operation. At low sparger slurry rates (0.1 m/s), depending on the gas rate, bubbles were visibly large, level control was difficult and reject overflow was inconsistent. This indicates that a minimum slurry velocity in the static mixer is required to ensure stable operation. For a gas rate of 1.5 cm/s it was found that the minimum pulp rate of was 0.3 m/s to obtain overflow at a froth depth of 65 cm while a pulp rate of 0.16 m/s was required for overflow at a gas rate of 2.5 m/s. The maximum attainable flow rate depended on the gas rate used. At velocities over 1.1 m/s and gas rates up to 2.5 cm/s, operation of the column and air sparging system became difficult due to pump flow variations. This was probably caused by air bubbles being entrained into the feed line of the sparging system.

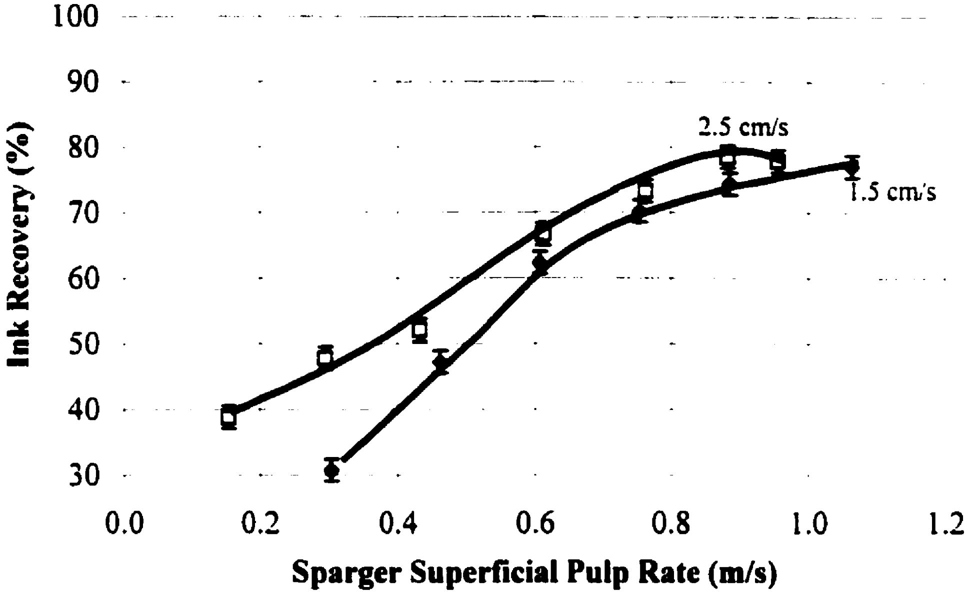


Figure 6.14 Ink recovery versus sparger superficial slurry rate at two superficial air rates. Conditions: retention time = 5 min; froth depth = 65 cm; column height = 4.65 m; bias rate = 0.15 cm/s.

As sparger pulp rate (gas rate = 2.5 cm/s) was changed from 0.2 m/s to over 1 m/s it was found that ink recovery increased to a maximum (approximately 80 %). A plateau was not reached test at a gas rate of 1.5 cm/s which continued to climb to about 80 % ink recovery. The increase in ink recovery as sparger pulp rate is increased is related to smaller bubble sizes and therefore higher bubble surface area rates. The bubble surface area rate is important because it governs the solids removal rate of the column. This is confirmed in Figure 6.15 which shows, in the case of a gas rate of 2.5 cm/s, that when the sparger pulp rate is increased from 0.2 m/s to over 0.9 m/s, bubble size decreases and a higher bubble surface area rate results. Meyer (1994) reported that by increasing the recycle rate (i.e., sparger pulp rate) chalcocite recovery increased during testing of a feed line aerated column. He hypothesized that recovery increased due to more bubble surface being available. Another reason why ink recovery increases as sparger superficial slurry rate increases maybe due to increased mechanical action in the mixer. Lascar (1991) found that the mechanical action in flotation cells promoted ink detachment from the fiber surface. One reason for the optimum pulp rate at a gas rate of 2.5 cm/s is probably related to turbulence. At high pulp velocities and high gas rates, the turbulence may be, such that particle-bubble detachment occurs. This trend was also seen by Tortorelli et al. (1997) in testing of an external gas/particle contacting device.

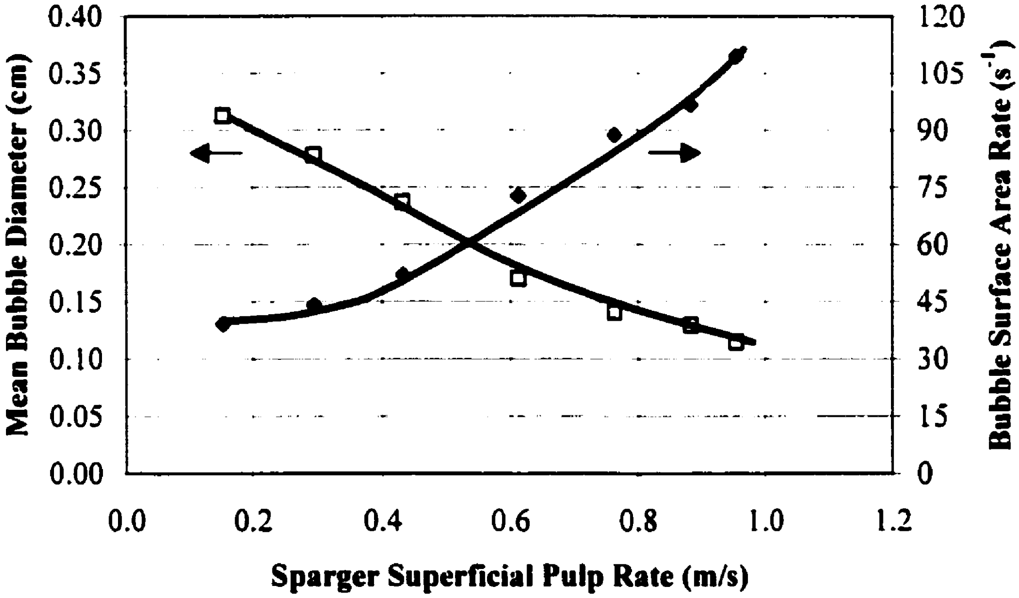


Figure 6.15 Sparger superficial slurry rate versus mean bubble diameter and bubble surface area rate. Conditions: retention time = 5 minutes, gas rate = 2.5 cm/s, froth depth = 65 cm; column height = 4.65 m; bias rate = 0.15 cm/s.

Organic loss followed the same trend as ink recovery (Figure 6.16). For a gas rate of 2.5 cm/s it followed an almost exponential increase, from approximately 1 % to almost 5 % at a pulp rate of 0.9 m/s. The organic loss trend at a gas rate of 1.5 cm/s was similar until a velocity 0.6 m/s was reached. Above this point, the curve flattened. The reason for this is not known. At the time when the optimum static mixer sparger slurry rate had to be chosen the organic losses were not know. This meant that a sparger slurry rate of 0.9 m/s was chosen on the basis solely of good ink recovery.

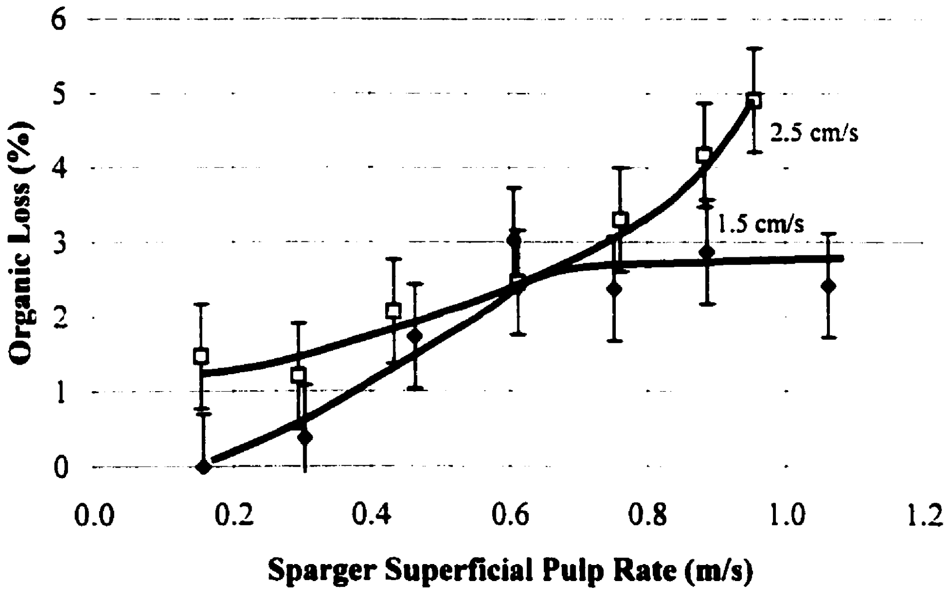


Figure 6.16 Organic loss versus sparger superficial slurry rate at two superficial air rates. Conditions: see Figure 6.14.

6.5.2.4 The Effect of Column Height

The effect of flotation column height on ink recovery and organic loss with all other variables kept constant except feed rate, is shown in Figure 6.17 and Figure 6.18, respectively.

Height had little impact on ink recovery with the 4.65 m column giving statistically similar results to the 3.1 m column. This is the same finding as for the porous sparger. In terms of organic losses, both column heights gave the same trend with differences being statistically insignificant. The selected column height for future work was 3.1 m.

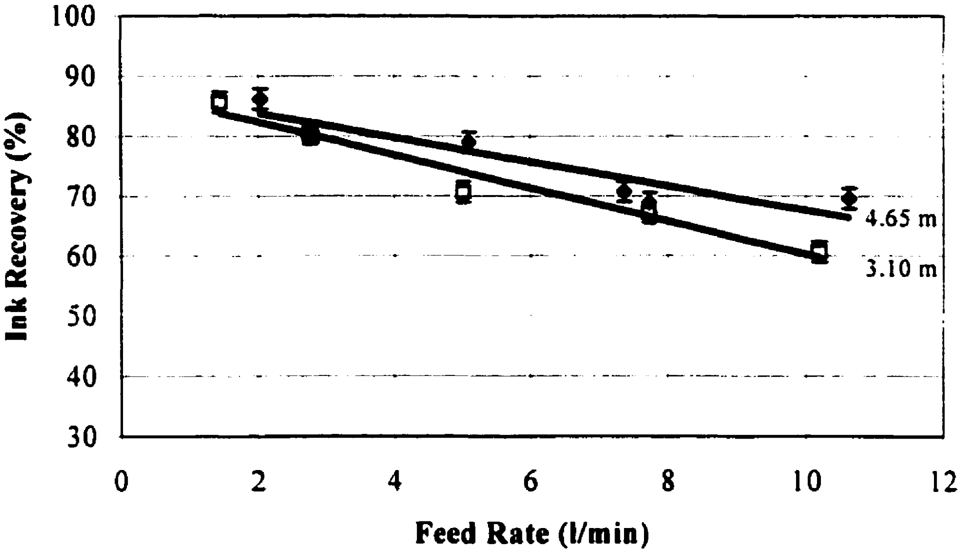


Figure 6.17 Ink recovery versus feed rate at two column heights. Conditions: air rate = 1.5 cm/s; froth depth = 65 cm; sparger pulp rate = 0.9 m/s; bias rate = 0.17 cm/s.

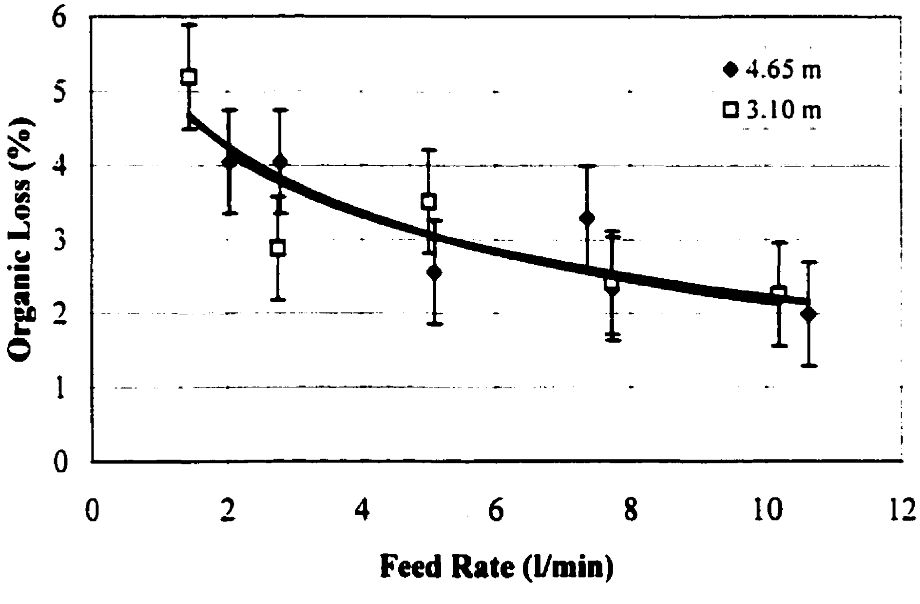


Figure 6.18 Organic loss versus feed rate at two column heights. Conditions: see Figure 6.17.

6.6 COMPARISON OF THE SPARGING SYSTEMS AND THE PLANT

The papermaking fibers exiting from the deinking plant should have the cleanliness, brightness and organic yield that are required for the final product. This section describes several ways to characterize the efficiency of the flotation process that will be used to compare the air sparging systems and Bowater's flotation circuit.

6.6.1 Ink Recovery - Reject Rate Relationship

Two key objectives of the deinking process are to maximize contaminant removal and to minimize the amount of rejects (thereby maximizing the accept yield). In the pulp and paper industry, the relationship between these two parameters are traditionally plotted as in Figure 6.19 which is reminiscent to the recovery-yield curve typically plotted in mineral processing. The ideal or perfect separation (100 % ink removal at 0 % rejects rate) is the point at the top left-hand corner of the graph. Although it can be never attained, it acts as a focal point, and the closer a system can approach it, the higher the efficiency. Normally, the reject rate (x-axis) refers to the mass reject rate of moisture-free pulp. However, it is common to also see reject rates of volume flow, fiber fractions and ash plotted on the x-axis as well (McCool, 1993).

Figure 6.19 shows the ink recovery-reject rate relationship for all tests in this thesis as well as four sampling campaigns across the Bowater flotation circuit (Plant Survey #1, Appendix E). In the present case, the x-axis corresponds to the reject flow rate as a percent of the feed rate. Figure 6.19 shows that a similar relationship is obtained for all tests using the two air sparging techniques. Tests with the static mixer sparger and porous sparger look to be slightly more efficient (closer to the top left-hand corner) than the Bowater circuit. However, the scatter in the test data and the fact that only four sampling campaigns of the plant circuit were done means that no difference can be supported. But, it should be emphasized, the Bowater flotation circuit involves six primary cells and two cells for fiber recovery where as the column was operated as a single unit.

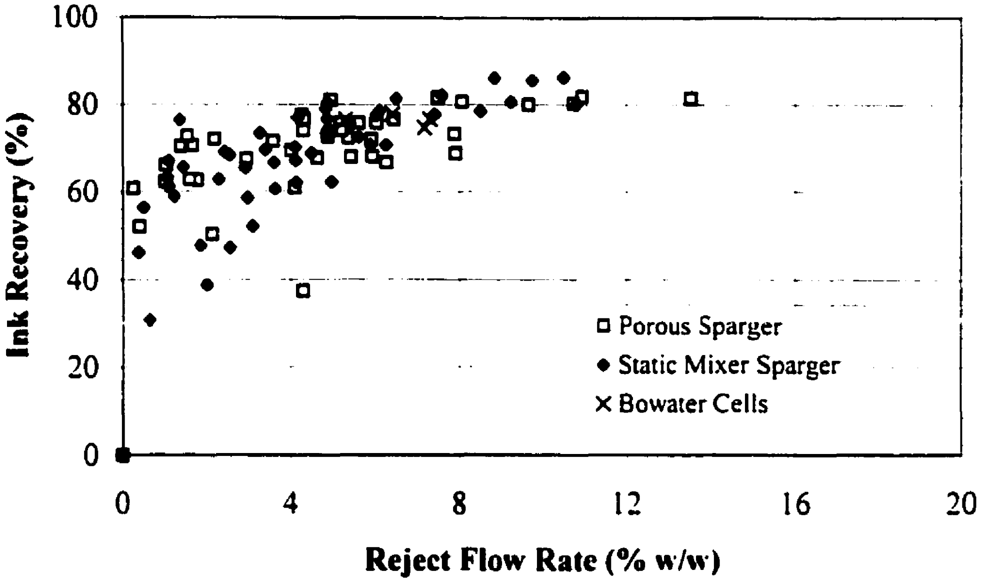


Figure 6.19 Ink recovery versus reject flow rate for both air sparging systems and Bowater's flotation circuit. Plant conditions: See Survey #1, Appendix E.

6.6.2 Organic Yield - Ink Recovery Relationship

There is an approximate inverse relationship between recovery and grade of concentrate in all concentrating processes. Concentrate grade and recovery, used simultaneously, are the most widely accepted measures of evaluating the performance of mineral separation systems (Wills, 1992). In flotation deinking, a similar relationship can be plotted with organic yield on the y-axis and ink recovery on the x-axis. This method of comparison is slightly more tedious than that previously used (Section 6.6.1) because the organic content of each stream has to be measured in order to calculate the overall organic yield. Figure 6.20 is an organic yield-ink recovery curve for all tests and the Bowater flotation circuit. It can be seen, like a traditional recovery-grade curve, that as ink recovery increases organic yield decreases and vise versa. To a first approximation all forms of column operation follow the same relationship regardless of sparger system used, and giving slightly better results (higher organic yields at comparable ink recoveries) than the plant. This could be attributed to the columns use of wash water which reduces entrainment and thus fiber losses.

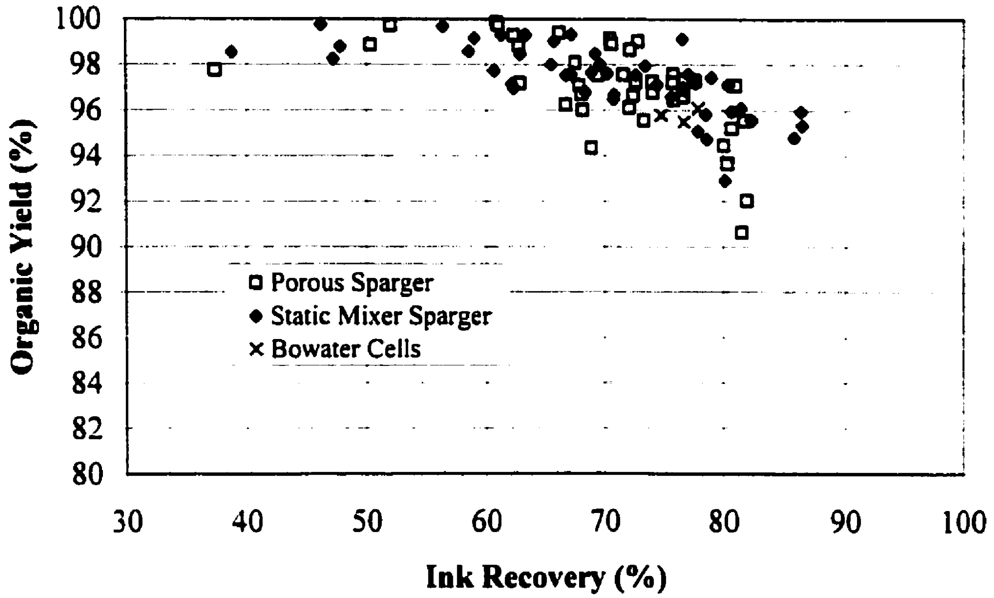


Figure 6.20 Organic yield versus ink recovery for both air sparging systems and Bowater's flotation circuit. Plant conditions: See Survey #1, Appendix E.

6.6.3 Superficial Bubble Surface Area Rate

The superficial bubble surface area rate (S_b) is the parameter that governs the solids removal rate of any flotation system. By increasing the bubble surface area available for particle attachment more solids will be removed. Bubble surface area rate is a useful basis for comparison because it incorporates both bubble size and gas rate into a single parameter (Equation 4.6).

Figure 6.21 shows the effect of bubble surface area rate on the ink recovery for all tests done with both air sparging systems. It can be seen that there is a general relationship between the ink recovery of the flotation column and the bubble surface area rate produced by the air sparging systems. Both sparging systems produced essentially the same relationship. For both spargers, a minimum bubble surface area rate of approximately 20 s^{-1} was required before the flotation column produced overflow for a froth depth of 65 cm. As the bubble surface area rate was increased, ink recovery increased rapidly. At a bubble surface area rate of 90 s^{-1} the ink recovery starts to plateau at approximately 80-85 %. This probably represents the maximum achievable ink recovery. A similar bubble surface area rate of ca 100 s^{-1} to achieve maximum recovery was reported by Leichtle (1998) in a 50 cm diameter column using porous spargers.

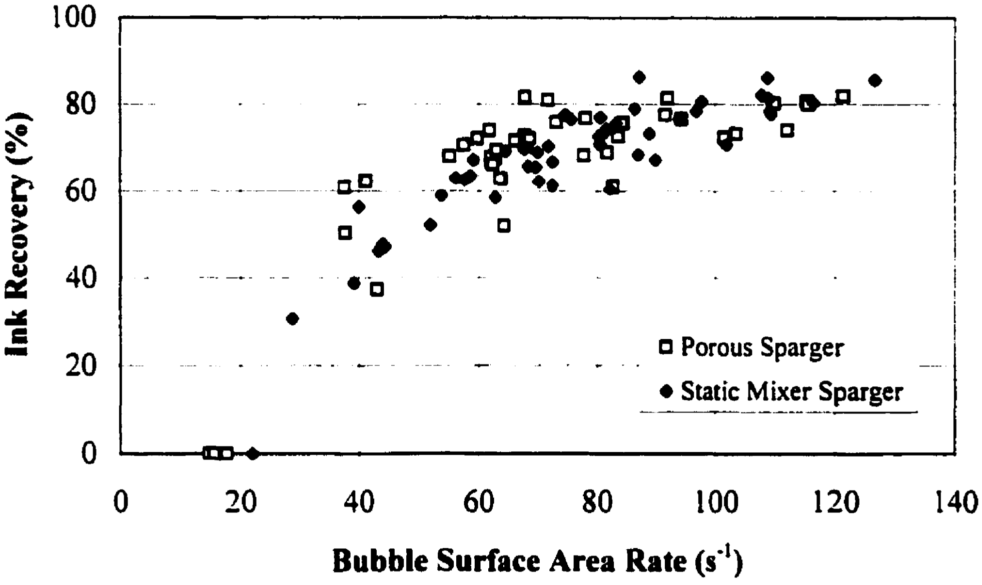


Figure 6.21 Ink recovery versus bubble surface area rate for both air sparging systems. Conditions: See appendices.

Figure 6.22 shows the effect of bubble surface area rate on organic loss. In both cases, organic loss increases with bubble surface area rate with the static mixer sparger giving slightly lower organic losses at equivalent bubble surface area rates. Several mechanisms that contribute to organic losses were described in Section 4.4.1. This work suggests that the organic loss is primarily due to the entrainment mechanism. As higher surface area rates are used, more fibers are being carried in the water accompanying the bubbles into the froth zone. Even though wash water is used, increased amount of fibers will report to the overflow and contribute to higher organic loss.

In summary, one of the most significant results obtained from this work is that the ink recovery and organic loss / bubble surface area rate relationship is independent of the sparging system used. This indicates that if different sparging systems can generate the same bubble surface area rate, they may recover the same amount of ink and fiber. The parallel work by Leichtle (1998) comparing different internal spargers (filter cloth, porous metal and jetting) led to the same conclusion.

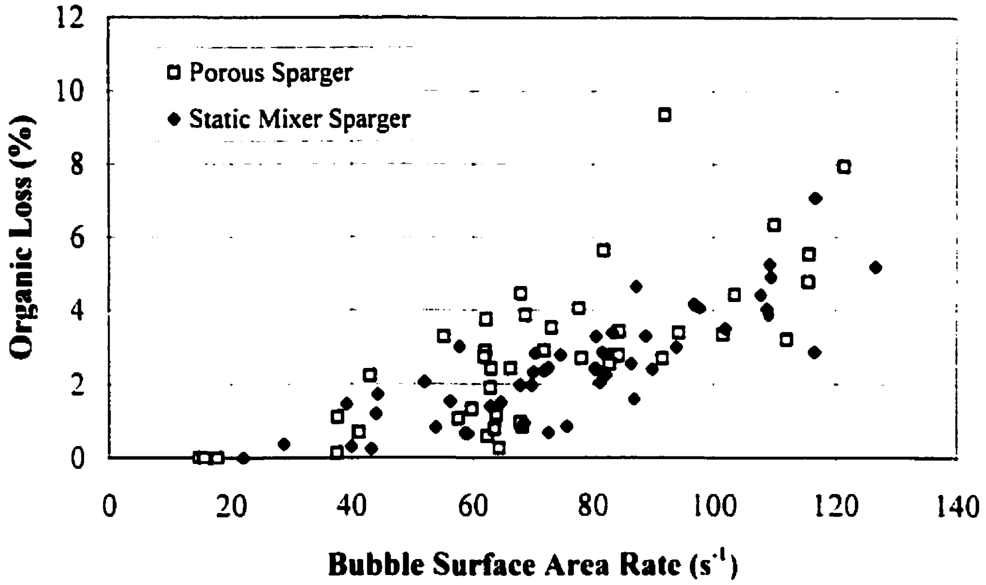


Figure 6.22 Organic loss versus bubble surface area rate for both air sparging systems. Conditions: See Appendices B and C.

6.7 LONG-TERM COMPARISON

The two air sparging systems were operated at their selected conditions (Table 6.4) and compared to Bowater's flotation circuit. Bias rate was maintained by controlling the wash water. The spargers were run for approximately 6 hours with 7 samples being collected and analyzed. All experiments were completed during a 30 hour period so that the feed from the plant would remain relatively constant to permit a comparison. All results for the long term tests are summarized in Appendix D. Samples from the mill flotation circuit were taken during testing of the static mixer sparging system (Plant Survey #2, Appendix E).

Table 6.4 Summary of selected operating conditions for each air sparging system.

Sparging System	Air Rate (cm/s)	Residence Time (min)	Sparger Rate (cm/s)	Column Height (m)	Froth Depth (cm)	Bias Rate (cm/s)
Porous	2.5	5	---	3.10	65	0.1
Static Mixer	2.5	4	30	3.10	65	0.1

The motivation for these tests was to see how stable the sparging system operation was over time. Experience in mineral flotation and deinking have shown that porous spargers have a tendency to plug over long term operation. As shown in Table 6.4 the selected operating conditions for each sparging system are the same except for the residence time. This indicates that the choice of sparging system was not a factor in achieving short term results. Figure 6.23 shows the bubble surface area rate (S_b) produced by both sparging systems over 6 hours of operation.

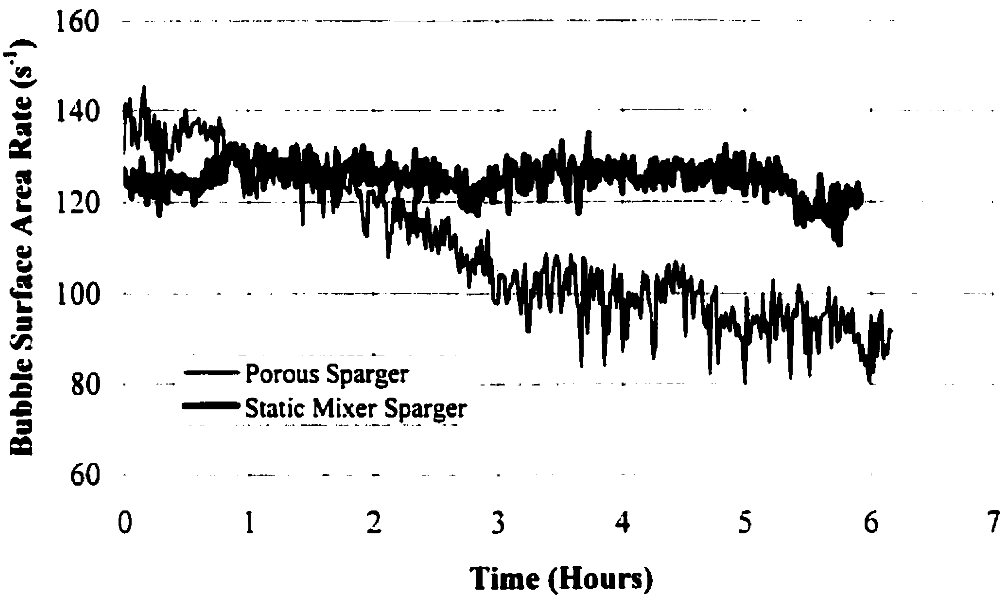


Figure 6.23 Bubble surface area rate versus time for long term testing of both air sparging systems. Conditions: See Appendix D.

This figure shows that the static mixer sparger was much more stable in operation than the porous sparger over the test period. The figure also shows that fairly high S_b's were produced by both sparging systems (at least initially for the porous sparger case) when compared to previous values. This may mean the flotation feed had slightly higher dosages of surfactant than at other times. The porous sparger initially gave a higher S_b (135 s^{-1}) than the static mixer sparger (125 s^{-1}) but decreased steadily over time to 90 s^{-1} while the static mixer sparger S_b remained constant (ca 120-125 s^{-1}). This meant that something was interfering with the bubble production process in the porous sparger, probably plugging. This tendency of the porous metal sparger to plug was previously noted by Watson (1996) and Leichtle (1998). After testing, a build-up on the porous rigid sparger was observed and a sample was collected and analyzed. An ashing test revealed that almost 40 % of the material was ash compared to the feed material which had a typical ash content of 10 - 15 %. This lead to the conclusion that perhaps the material plugging the sparger was fine mineral particles used in coatings on magazine paper. Typical coatings used in the pulp and paper industry contain high amounts of kaolinite clay and calcite. Ink recovery for the two spargers and Bowater's flotation circuit versus time is shown in Figure 6.24.

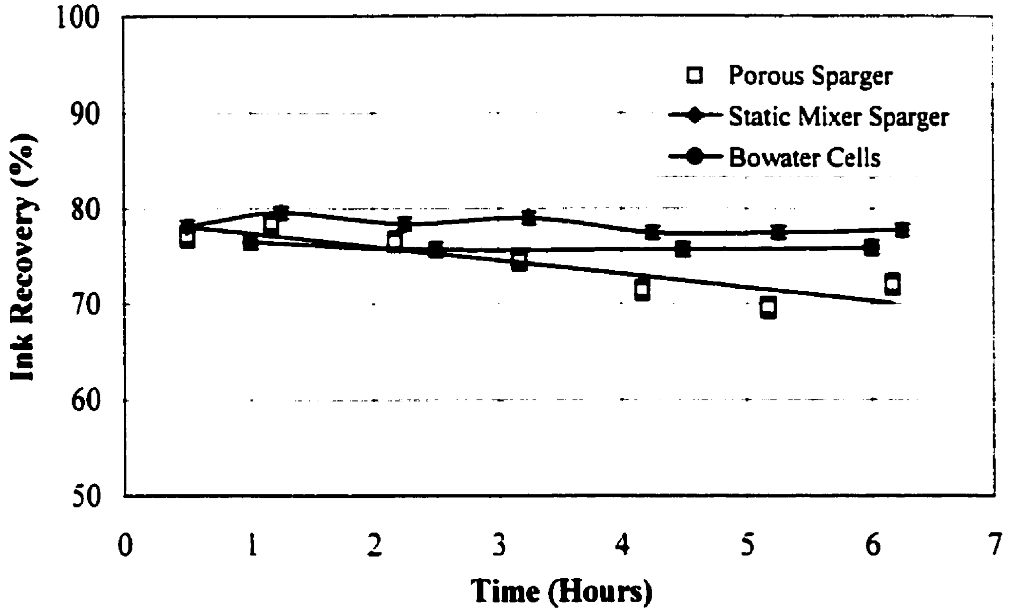


Figure 6.24 Ink recovery versus time for long term testing of both air sparging systems and Bowater's flotation circuit. Conditions: See Appendices D and E.

In Section 6.6.3, ink recovery and organic yield were related to the bubble surface area rate. Figure 6.24 shows that the ink recovery for the static mixer was stable and high (ca 77 % to 88 % and generally exceeding the plant) which corresponds to the high and constant S_b (120-125 s^{-1}). The porous sparger result further confirmed that the ink recovery is related to bubble surface area rate by falling from 78 % to 72 % as the S_b decreased. Figure 6.25 shows the corresponding organic loss.

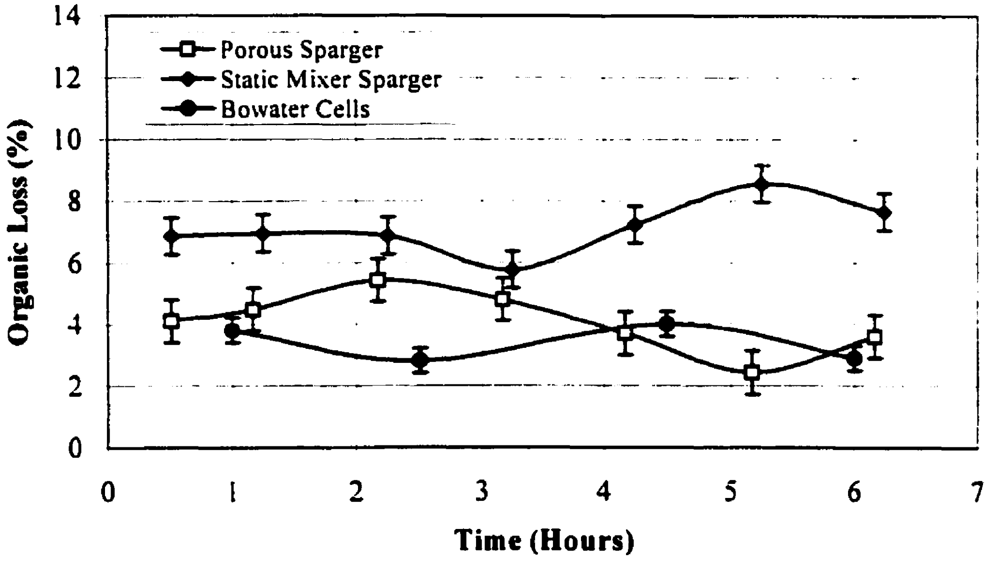


Figure 6.25 Organic loss versus time for long term testing of both air sparging systems and Bowater's flotation circuit. Conditions: See Appendices D and E.

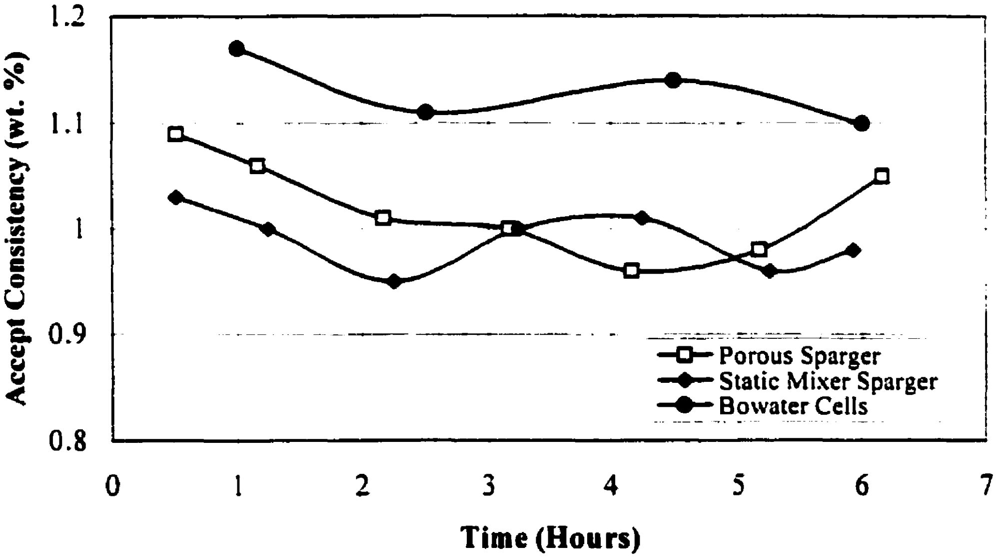


Figure 6.26 Accept consistency versus time for long term testing of both air sparging systems and Bowater's flotation circuit. Conditions: See Appendices D and E.

Correlating organic loss with bubble surface area rate was not obvious. This may be an artifact of the mass balancing process or differences in flotation cell consistency (Figure 6.26) which could not be controlled. However, overall trends could be defined with the static mixer giving the highest organic losses (7 %) while the other two systems had similar organic losses of approximately 4 %. The 7 % loss with the static mixer is in accord with the bubble surface area rate of 120-125 s^{-1} (Figure 6.22).

Table 6.5 shows the results of the long term tests using the two sparging systems and the performance of Bowater's flotation circuit. Over the long term, the static mixer sparger produced the highest mean ink recovery, followed by Bowater's flotation circuit and the porous sparger. The static mixer sparger gave the highest organic losses followed by the porous sparger and the Bowater circuit, which gave almost identical losses. Organic losses for the static mixer sparger could be improved in subsequent tests by decreasing the S_b to approximately 100 s^{-1} (to minimize entrainment and allow good ink recovery) and changing the wash water rate.

Table 6.5 Average ink recovery and organic losses for the two air sparging systems and Bowater's flotation circuit. Variation is given as a 90 % confidence interval.

Flotation System	Sparging System	Ink Recovery			Organic Loss		
		Mean (%)	+/-	Std Dev.	Mean (%)	+/-	Std Dev.
Lab Column	Porous	74.2	1.0*	1.5*	4.1	0.7	1.0
Lab Column	Static Mixer	78.3	0.6	0.8	7.1	0.6	0.9
Bowater	---	75.8	0.7	0.7	4.2	0.4	0.4

* Values based on a decreasing trend line, see text.

The mean ink recovery for the porous sparger is the mean of all values obtained and is not an accurate indication of its overall performance as it is continuously decreasing. To show the decreasing performance trend, a negative sloping line (R_{ink}= 78.81-1.42×time) was fit to the data points. This was then used to obtain the 90 % confidence interval and standard deviation of the measured value from the trend.

6.9 COMPARISON TO PREVIOUS STUDIES

Some comparisons with previous column flotation studies and the results of this study were described in Sections 6.4 and 6.5. This section attempts to detect differences from this 1998 study to previous work at the same deinking facility in 1996 (Watson, 1996). The 1996 work initially indicated large differences. this however was found to be a result of differences in bubble size estimation techniques. Figure 6.27 compares the current results to those of Watson in terms of the bubble surface area rate (recalculated) and ink recovery relationship. The data by Watson (Appendix F) includes results from two different pore diameter spargers (0.5 μm and 100 μm) and for short and long term tests.

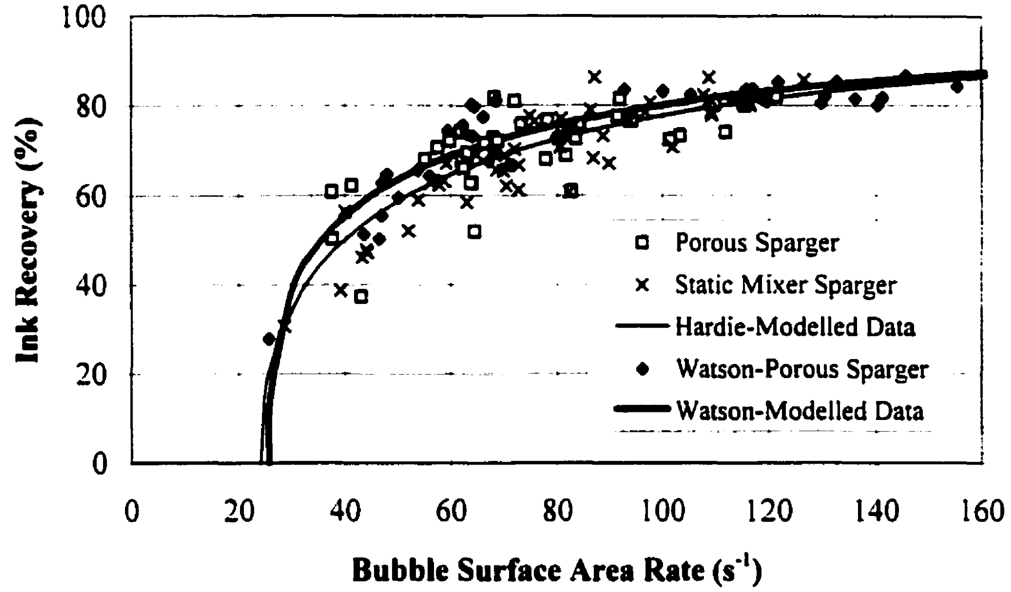


Figure 6.27 Bubble surface area rate versus ink recovery for all flotation tests and Watson (1996) results. Conditions: See Appendix F.

The data suggest that the two sets of results gave virtually identical relationships. In an attempt to test if there were differences, the data were fitted by a least squares method (Microsoft Excel Solver Function) using a modified equation similar to the traditional model used in mineral processing to characterize hydrocyclone classifier efficiency (Plitt, 1976). The modified equation relating the percentage of ink recovery (R_{model}) to bubble surface area rate (S_b) is as follows:

$$R_{model} = 100 \cdot \left[1 - \exp\left(-0.693\right)\left(\frac{S_b - S_{b\min}}{S_{b50} - S_{b\min}}\right)^m \right] \qquad 6.1$$

where $S_{b\min}$ is the minimum bubble surface area rate to obtain overflow, S_{b50} is the bubble surface area rate to recover 50 % of the ink and m describes the sharpness of the separation curve. During the modeling process, differences in sparging system type and operation were ignored (See Section 6.6.3). Table 6.6 shows the parameters and goodness of fit that were obtained by fitting the modified hydrocyclone equation to both sets of data.

Table 6.6 Modeling results using the modified hydrocyclone equation (Equation 1).

Test Data	Fitted Parameters			Number of Tests	$\Sigma(R_{actual}-R_{model})^2$
	S_{b50}	S_{bmin}	m		
Hardie (1998)	40	24	0.49	87	3046
Watson (1996)	36	25	0.42	49	818

The modeling results show that the ink recovery/bubble surface area rate relationship for both data sets are similar with the only noticeable difference being in the S_{b50} value. The S_{b50} for the test work done in 1996 was slightly lower (36 s^{-1}) than for the test work in 1998 (40 s^{-1}). This may be related to flotation chemistry as numerous changes have been made since 1996 to reduce chemical costs (Dionne, 1997 and Akzo Nobel, 1998). Therefore, at the present, perhaps a slightly higher bubble surface rate is required to compensate for reduced ink floatability. The other fitted parameters S_{bmin} and m are similar and do not indicate any obvious differences between tests done in 1996 and 1998. The goodness of fit between the model and their respective data set is shown by the sum of the squares of the differences ($\Sigma(R_{actual}-R_{model})^2$) with a lower value indicating a better fit. These values are in the 6th column of Table 6.6. The 1996 data fit the model better (818) than the 1998 data (3046) due to less data scatter. However, the number of points in the data also influences this result. Subsequent division of ($\Sigma(R_{actual}-R_{model})^2$) value by the number of data points still indicates that the 1996 data fits better.

Figure 6.28 shows the bubble surface area rate/organic loss relationship for all tests in this thesis as well as the results from Watson (1996). A model was not developed for this relationship as the previous modelling attempt showed little difference between 1998 and 1996 experiments. The graph shows a general trend with the previous work probably producing lower organic losses at bubble surface area rates above 100 s^{-1}. This is shown, for example at 120 s^{-1}, where Watson's organic losses rarely exceeded 4 % while organic losses for this work showed a trend towards 8 %. This might also be a response to changes in plant chemistry. For example, as described in Section 4.4.1, it has been shown that increases in the water hardness (calcium ion concentration) increases the hydrophobicity of fibers and thus their flotability (Turvey,1993).

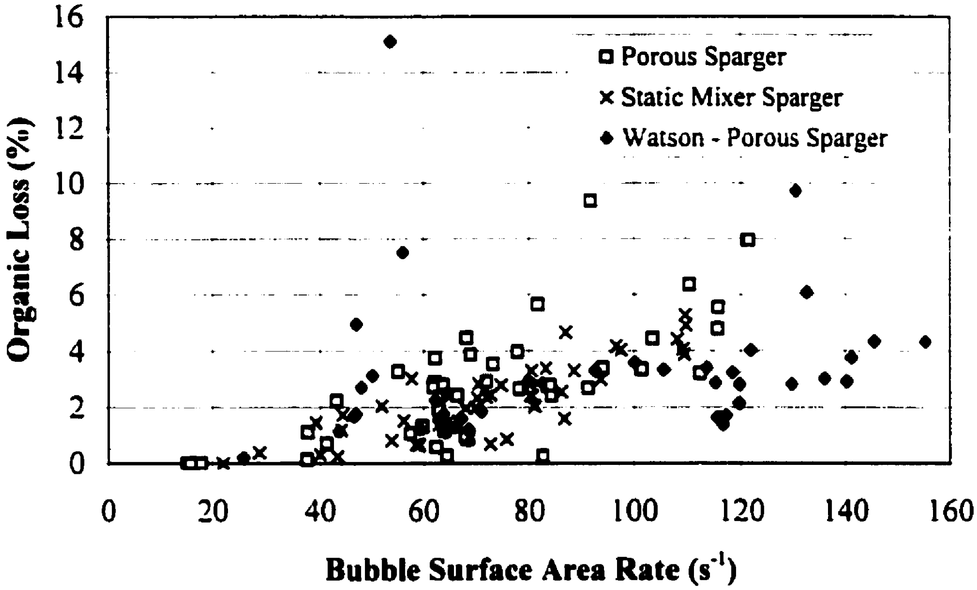


Figure 6.28 Bubble surface area rate versus organic loss for all flotation tests and Watson (1996) results. Conditions: See Appendices B, C and F.

To compare the relationship between fiber loss and ink recovery for both data sets, the results were plotted in terms of organic yield/ink recovery (Figure 6.29). An arbitrary zone (darkened box) based on a good separation (80 % to 90 % ink recovery at 97 % to 99 % organic yield) was created to provide a target area for column operation. In 1996 some tests has performance in the target area. No results from the 1998 campaign fell in this area. This fact may indicate that the chemistry in 1996 was slightly better in terms of creating conditions conducive to promoting separation of ink particles from paper fiber.

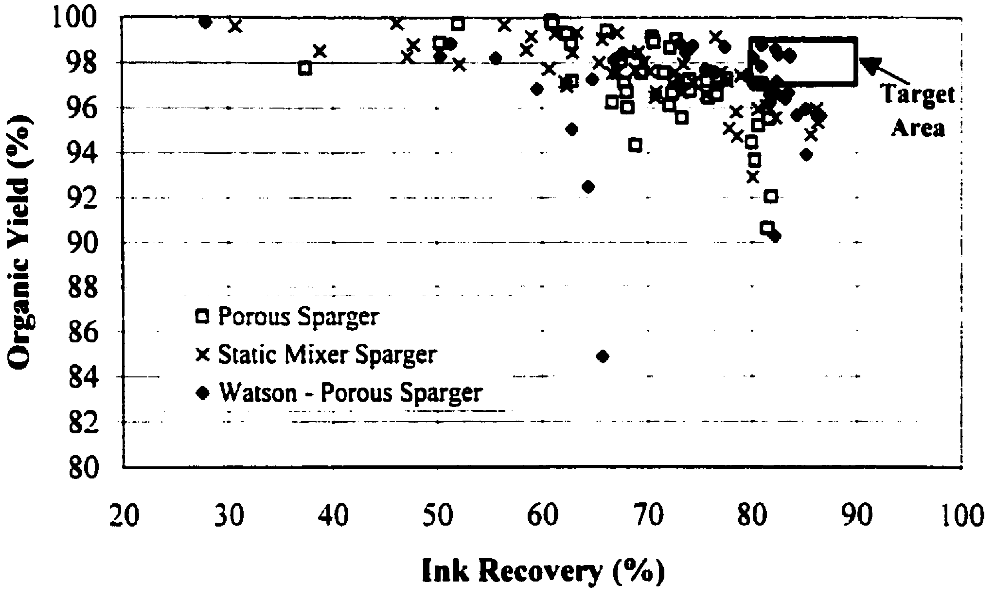


Figure 6.29 Organic yield versus ink recovery for all flotation tests and Watson (1996) results. Conditions: see Appendices B, C and F.

6.8 COLUMN SCALE-UP RESULTS

Two companies were contacted to provide a preliminary sizing and cost estimation of a flotation column installation to treat Bowater's mill throughput of 600 mtpd at 1.3 wt. % solids. Company A specializes in flotation columns with conventional internal sparging systems (porous and jetting) while Company B provides columns with air sparging systems similar to the static mixer sparger used in this test program. Both companies were requested to scale up a column circuit based on the results of the long term tests which are shown in Appendix D. No other information was given as to circuit design, maximum column height etc. An average of all data was used in the case of the static mixer sparger tests while an average of the last 3 samples (2 hours) was used in the case of the porous sparger due to plugging problems.

6.8.1 Option 1: Column with Internal Air Sparging System

A total of 4 columns, 3.5 m in diameter by 14 m tall (floor to lip), are required in this proposal to achieve the required ink recovery of 85 % (% of maximum) as obtained in the lab column test work. The calculated lab column rate constants based on the company's scale-up routines were 0.7 minute^{-1} for the ink flotation and 0.013 minute^{-1} for the fiber flotation. This design was the more innovative in terms of circuit arrangement (Figure 6.30).

The circuit was divided into two parallel lines capable of treating 300 tpd each. Each line included two cells in series, with the accepts from cell 1 feeding cell 2, and the rejects from cell 2 being recycled to the feed of cell 1. The estimated capital cost for the four columns is \$600,000. This cost estimate includes engineering, fabrication (with mild steel), painting, quality control and spargers. Additional costs for average air, wash water and level control systems would be \$40,000 per column. Installation of the columns and an air compressor system are extra costs, which were not included in the proposal. Overall, the cost per column is approximately \$190,000.

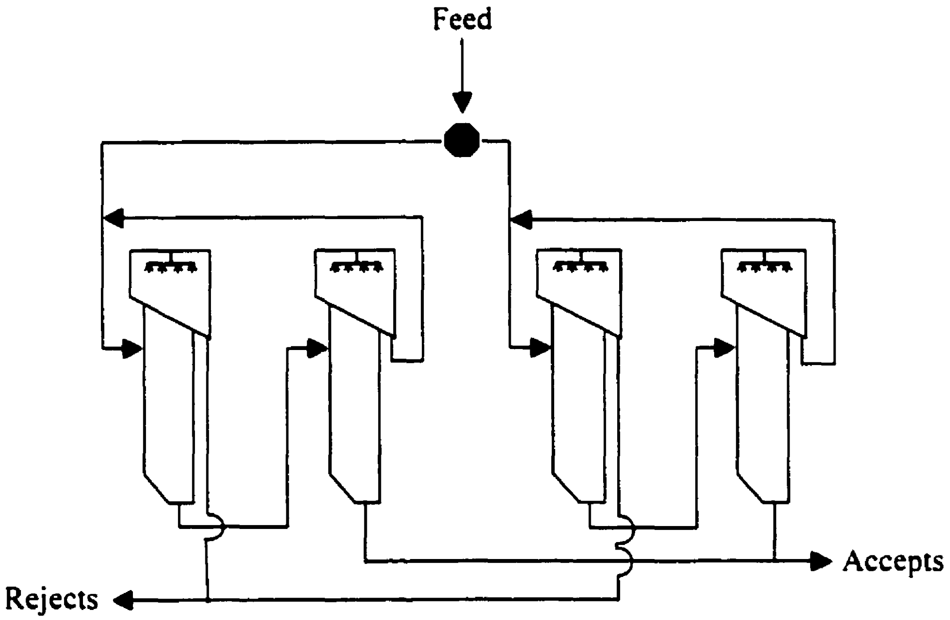


Figure 6.30 Two lines of columns in CC/scavenger-closed circuit arrangement.

6.8.2 Option 2: Column with Static Mixer Air Sparging System

A total of 6 columns 4.15 m in diameter and 9.15 m in height, are required in this proposal to achieve an ink recovery of 92.5 % (% of maximum) as obtained in the lab column test work. In this proposal, a circuit design was not mentioned other than that the columns could be split into two lines of three in parallel (Figure 6.31) so that some flexibility in terms of production could be obtained. All cost estimates were given in U.S.

dollars therefore a Canadian equivalent was calculated using a conservative exchange rate of 1.4.

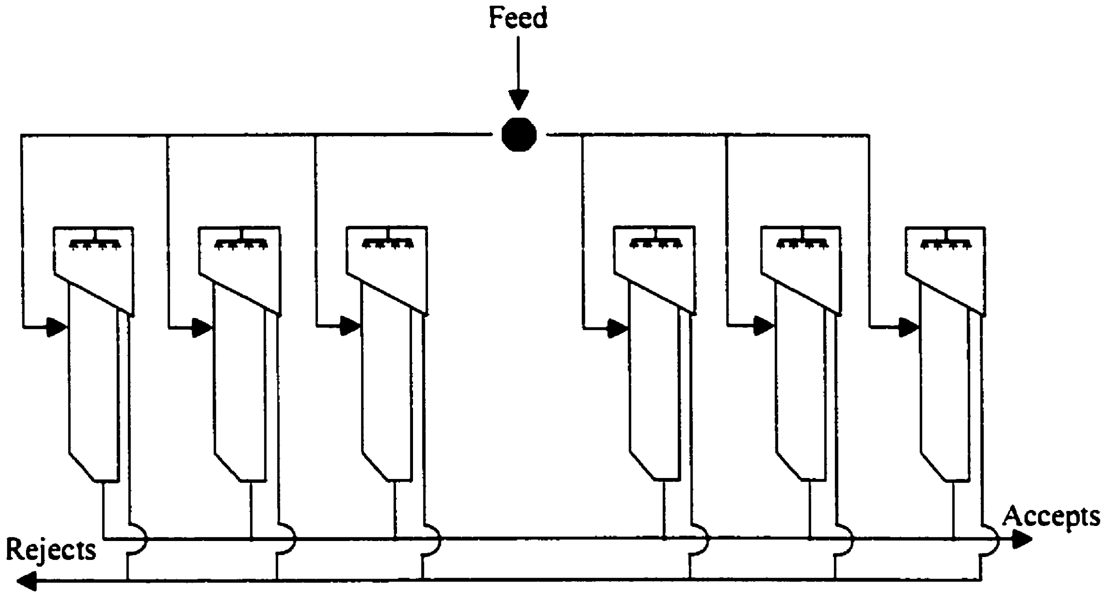


Figure 6.31 Two lines of three columns in parallel.

The sparging system for each column consists of a 10 x 12 centrifugal recycle pump with 12-14 static inline mixers 4 inches in diameter. The estimated price for this column installation (made of steel) is approximately $1,370,000 which includes variable frequency drive pumps, flow meters, sparging system, automatic air and wash water flow control. This price does not include installation or erection costs. The manufacturer also indicated that depending on the final design specification and desired options, a basic working system, at 10 - 20 % less than the estimated one could be provided. To build the columns out of stainless steel, a material often used in the pulp and paper industry, the manufacturer indicated that the cost would be increased by approximately $670,000. Overall, based on the quoted system, the cost per column is approximately $228,000.

6.8.3 Comparison of Column Scale-up Options

Due to the preliminary nature of the project and varying design philosophies of the two companies, exact comparisons based on these data cannot easily be made. The price per column for the static mixer sparging system is slightly higher due primarily to the requirement of a recycle pump. This was expected but should not be the sole criteria in deciding a final purchase. The initially higher capital costs may over the long run be more economic due to higher ink recoveries (93 % versus 85 % of maximum) and less maintenance due to problems with the air sparging system.

The choice of the flotation circuit design will also have a large influence on the final outcome. A circuit design for the static mixer system similar to Figure 6.30 could easily be worked out to reduce the number of columns from 6 to 4. In the end, it should be noted that the original Voith flotation circuit installation at Bowater cost approximately six million dollars (Watson et al., 1996) and that either type of column installation capable of treating the same feed would be significantly less.

✧ CHAPTER SEVEN ✧

Conclusions and Recommendations

7.1 CONCLUSIONS

A number of conclusions can be drawn from the studies performed to date. They are broken down as follows:

Batch Tests of Sparging Systems

1) The static mixer sparger at superficial liquid velocities of 0.9 m/s and higher in a 30 ppm Dowfroth 250C/water solution gave a similar J_g/E_g relationship when compared to the porous sparger (0.5 μm).

2) The static mixer sparger gave a similar J_g/E_g relationship in a 1.3 % consistency pulp solution when compared to the test done in Dowfroth 250C/water. The static mixer sparger when operated at velocities higher than 0.6 m/s outperformed the porous sparger in a 1.3 % consistency pulp. This was attributed to fiber flocculation during the porous sparger batch test.

Statistical Analysis and Experimental Error

3) All measurements of column conditions gave relative standard deviations less than 5 % except for those dealing with the rejects stream. The higher relative standard deviations for the rejects stream (10-20 %) were a result of bubble movement and a build up/ overflow action in the froth zone.

4) The 90 % confidence interval for ink recovery was ± 1.8 % and for organic loss. ± 0.7 %.

Determination of Operating Parameters - Porous Sparger

5) The optimum pulp retention time for ink recovery was 6 minutes. At times longer than this organic losses began to increase exponentially.

6) Gas rate had a large effect on ink recovery and organic loss. Both increased as the gas rate was increased. At gas rates above 2.5 cm/s to 3 cm/s column operation became difficult.

7) Wash water had little effect on ink recovery. Organic losses decreased as wash water increased. This was attributed to a reduction in entrained fibers.

8) Froth depth had little effect on ink recovery. Organic losses decreased as froth depth was increased.

9) Column heights (3.1 m and 4.65 m) gave statistically similar results.

Determination of Operation Parameters - Static Mixer Sparger

10) The effect of pulp retention time and gas rate had the same relationship in terms of ink recovery and organic loss as the porous sparger.

11) At a given air rate, ink recovery and organic losses increased as the sparger pulp rate was increased.

12) Varying the velocity of pulp through the static inline mixer gave control over bubble size and thus superficial bubble surface area rate. The static mixer sparger operating range was determined to be between 0.2 m/s and 1.1 m/s depending on the gas rate utilized.

13) Column height had little effect on ink recovery and organic loss, similar to the porous sparger.

Long Term Tests

14) The static mixer system (R_{ink}= 78.3 %) outperformed both the Bowater flotation circuit (R_{ink}= 75.9 %) and the column with the porous sparging system (R_{ink}= 74.3 %) in terms of average ink recovery over a 7 hour period. However, the static mixer sparger also gave the highest organic losses of the three systems tested (7.1 % versus 3.3 % and 4 %, respectively).

15) No operational problems were encountered with the static mixer air sparging system over the 7 hours of continuous testing.

16) Ink recovery with the porous sparging system decreased over time. This was attributed to plugging of the sparger and the resulting decrease in available bubble surface area.

17) The source of the plugging material was determined to fine mineral particles which are typically used as filler in magazines.

Overall Conclusions- Sparger Comparison

18) Continuous testing with pulp confirmed the J_g/ε_g relationship that was obtained in batch conditions with Dowfroth 250C and water. The static mixer sparging system was able to produce the same bubble surface area rate (S_b) as the porous sparger.

19) During testing of both air sparging systems. as S_b was increased ink recovery increased and until a plateau of approximately 85 % was reached. Organic losses, on the other hand, continuously increased to over 6 %. Both spargers produced the same S_b/ink recovery and organic loss relationship.

20) A minimum S_b of approximately 20 s^{-1} is required for reject overflow at a froth depth of 65 cm. and approximately 100 s^{-1} is required to match the ink recovery of the plant flotation circuit.

21) The selection of one air sparging system over the other should be based on operational stability and on a cost per unit bubble surface area rate produced.

Comparisons with Previous Studies and Bowater Plant

22) Bowater's flotation circuit which consists of a 6+2 Voith cell arrangement had an ink recovery of 76.2 % (standard deviation 0.92) and a organic loss of 3.7 % (standard deviation 0.72) as determined by two plant surveys.

23) The ink recovery/organic loss relationship (similar to the mineral system grade/recovery curve) was shown to useful for comparing flotation deinking systems.

24) A model based classifier efficiency was used to describe the S_b/ink recovery relationship. The model indicated little difference in ink recovery from previous flotation studies Watson (1996) and the present work. Previous differences were attributed inconsistencies in the drift flux analysis method.

25) The present work produced slightly higher organic losses at equivalent S_b's compared to Watson's (1996) data. This was attributed to slight differences in mill chemistry.

Scale-Up Results

26) Differences in the two company's design philosophies made it difficult to directly compare their scale-up proposals. More detailed proposals are required to accurately determine their advantages and disadvantages.

27) On a per column basis, estimates indicated that columns equipped with an internal sparging system are slightly less expensive than a column with a static mixer sparging system.

28) A deinking circuit based on the static mixer system requires 6 columns (4.15 m in diameter by 9.15 m tall) in parallel while only 4 columns (3.5 m in diameter by 14 m tall) with an internal sparging system in a CC/scavenger arrangement are required to process Bowater's flow.

29) Initial capital costs, ink recovery and organic losses should not be the only factors used in determining the benefits of certain air sparging technologies. Some indication of the reliability and maintenance issues should be included as well.

30) Any column installation based on the two scale-up options would be cheaper than the existing Bowater flotation circuit.

7.2 RECOMMENDATIONS

1) Circuit simulation and testing to determine the effects of various circuit arrangements on ink recovery and particularly organic loss.

2) Determine the extent of particle collection in static mixer itself.

3) Perform fundamental experiments under controlled conditions to determine the effect of column height, froth depth and bias rate.

4) Perform experiments to determine whether flotation deinking columns require more or less chemicals compared to present flotation deinking technology.

5) Install a static mixer sparging system on a larger flotation column and run comparison tests against porous spargers and the mill flotation circuit. These would confirm lab scale results and provide scale-up data.

6) A detailed examination of the feed stream for the purpose of generating a theoretical organic yield/ink recovery curve would be beneficial.

7) Perform test experiments to determine the operating conditions and proper dimensions necessary to minimize the amount of air recirculation in the static mixer sparger system recycle pump.

8) Perform column flotation experiments on reject streams to determine the viability of the technology in reducing the fiber losses.

9) Determine whether the drift flux model can be directly applied to a pulp system without modification

10) Determine whether the scale-up equations used for mineral flotation columns can be directly applied to deinking flotation systems.

11) Perform an economic analysis to determine whether the slightly higher costs for installing a static mixer based sparger on a flotation column due to less maintenance.

❧ CHAPTER EIGHT ❧

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♈ APPENDICES ♈

BATCH TESTS

A-1 Batch tests done in water and 30 ppm Dowfroth 250C
A-2 Batch tests done in 1.3 % pulp

POROUS SPARGER TEST WORK (CODE: ISP)

B-1 Test conditions
B-2 Flotation efficiency and brightness gain results
B-3 Flow rate, consistency, organic content and standard deviation data
B-4 Material balanced data

STATIC MIXER SPARGER TEST WORK (CODE: M1V)

C-1 Test conditions
C-2 Flotation efficiency and brightness gain results
C-3 Flow rate. consistency. organic content and standard deviation data
C-4 Material balanced data

LONG TERM TEST WORK

D-1 Material balanced data
D-2 Scale up parameters based on long term tests

BOWATER FLOTATION CIRCUIT SURVEY

E-1 Material balanced data for surveys 1 and 2

WATSON (1996) COLUMN FLOTATION TEST WORK

F-1 Bubble size and superficial bubble surface area rate calculations
F-2 Flotation column test data for 0.5 µm and 100 µm porous spargers

A-1 Batch tests done in water and 30 ppm Dowfroth 250C

Test	Sparging	Sparger Pulp Flow		J_l	Air Flow	J_g	P2	P3	E_g	Corr. Air Flow	Corr. J_g	d_b (P2-P3)	S_b (P2-P3)
Series	Device	(L/min)	(m/s)	(cm/s)	(L/min, STP)	(cm/s, STP)	(cm H2O)	(cm H2O)	(%)	(L/min, P2-P3)	(cm/s, P2-P3)	(cm)	(s^{-1})
H-1	Static mixer	10.1	0.30	0.0	1.21	0.25	34.35	123.43	1.35	1.12	0.23	0.145	10.5
H-2	Static mixer	10.1	0.30	0.0	2.41	0.50	36.46	124.39	2.62	2.24	0.47	0.151	20.2
H-3	Static mixer	10.2	0.31	0.0	3.61	0.75	38.50	125.34	3.83	3.34	0.70	0.158	29.0
H-4	Static mixer	10.1	0.30	0.0	4.81	1.00	40.52	126.10	5.23	4.45	0.93	0.156	39.2
H-5	Static mixer	10.1	0.30	0.0	7.21	1.50	44.20	127.62	7.62	6.66	1.38	0.164	55.6
H-6	Static mixer	10.1	0.30	0.0	9.62	2.00	48.05	129.14	10.20	8.86	1.84	0.168	72.6
H-7	Static mixer	10.1	0.30	0.0	12.02	2.50	51.15	130.33	12.31	11.05	2.30	0.179	85.2
I-1	Static mixer	21.1	0.63	0.0	1.21	0.25	39.34	125.62	4.45	1.12	0.23	0.042	36.2
I-2	Static mixer	21.2	0.64	0.0	2.42	0.50	44.29	127.52	7.83	2.23	0.46	0.049	62.2
I-3	Static mixer	21.2	0.64	0.0	3.61	0.75	48.11	129.09	10.32	3.32	0.69	0.057	80.3
I-4	Static mixer	21.2	0.64	0.0	4.81	1.00	52.08	130.76	12.87	4.42	0.92	0.062	97.6
I-5	Static mixer	21.2	0.64	0.0	7.21	1.50	60.66	134.10	18.67	6.59	1.37	0.069	132.9
J-1	Static mixer	30.1	0.90	0.0	1.21	0.25	43.29	127.56	6.68	1.12	0.23	0.030	50.4
J-2	Static mixer	30.1	0.90	0.0	2.42	0.50	51.41	131.30	11.53	2.22	0.46	0.036	84.9
J-3	Static mixer	30.1	0.90	0.0	3.61	0.75	56.66	133.53	14.87	3.31	0.69	0.042	107.8
J-4	Static mixer	30.2	0.91	0.0	4.81	1.00	63.16	136.62	18.65	4.39	0.91	0.047	130.5
J-5	Static mixer	30.2	0.91	0.0	7.21	1.50	72.02	139.13	25.68	6.54	1.36	0.055	166.2
K-1	Static mixer	40	1.20	0.0	1.21	0.25	49.48	130.99	9.73	1.11	0.23	0.023	65.4
K-2	Static mixer	40.3	1.21	0.0	2.4	0.50	56.20	134.58	13.20	2.20	0.46	0.032	93.4
K-3	Static mixer	40	1.20	0.0	3.61	0.75	62.57	137.28	17.26	3.29	0.68	0.038	119.6
K-4	Static mixer	39	1.17	0.0	4.81	1.00	67.49	138.66	21.18	4.37	0.91	0.043	141.8
X-1	0.5 micron S.S	n/a	n/a	0.0	1.21	0.25	40.87	126.66	4.99	1.12	0.23	0.038	40.0
X-2	0.5 micron S.S.	n/a	n/a	0.0	2.41	0.50	50.76	131.38	10.72	2.21	0.46	0.038	80.4
X-3	0.5 micron S.S	n/a	n/a	0.0	3.61	0.75	59.03	135.04	15.83	3.30	0.69	0.040	112.7
X-4	0.5 micron S.S	n/a	n/a	0.0	4.81	1.00	69.17	138.9	22.78	4.37	0.91	0.041	148.0

A-2 Batch tests done in 1.3 % pulp

Test	Sparging	Pulp	Sparger Pulp Flow		J_l	Air Flow	J_g	P2	P3	E_g	Corr. Air Flow	Corr. J_g	d_b (P2-P3)	S_b (P2-P3)
Series	Device	(% solids)	(L/min)	(m/s)	(cm/s)	(L/min, STP)	(cm/s, STP)	(cm H2O)	(cm H2O)	(%)	(L/min, P2-P3)	(cm/s, P2-P3)	(cm)	(s^{-1})
L-1	static mixer	1.29	10.1	0.30	0.0	1.2	0.25	27.34	115.78	2.1	1.12	0.23	0.1	16.8
L-2	static mixer	1.29	10.2	0.31	0.0	2.4	0.50	28.83	116.41	3.0	2.24	0.47	0.1	23.4
L-3	static mixer	1.29	10.1	0.30	0.0	3.61	0.75	30.86	117.3	4.3	3.37	0.70	0.1	32.6
L-4	static mixer	1.29	10.2	0.31	0.0	4.81	1.00	32.6	118.12	5.3	4.48	0.93	0.2	39.4
L-5	static mixer	1.29	10.2	0.31	0.0	7.21	1.50	36.16	119.84	7.3	6.70	1.39	0.2	52.8
L-6	static mixer	1.29	10.2	0.31	0.0	9.62	2.00	39.46	121.19	9.5	8.93	1.86	0.2	66.6
L-7	static mixer	1.29	10.1	0.30	0.0	12.02	2.50	42.04	122.33	11.1	11.13	2.32	0.2	75.5
L-8	static mixer	1.29	10.1	0.30	0.0	14.43	3.00	44.29	123.19	12.6	13.35	2.78	0.2	83.8
M-1	static mixer	1.33	20.1	0.60	0.0	1.21	0.25	35.6	122.2	4.1	1.12	0.23	0.0	33.6
M-2	static mixer	1.33	20.1	0.60	0.0	2.41	0.50	40.62	124.71	6.9	2.23	0.46	0.1	55.3
M-3	static mixer	1.33	20.1	0.60	0.0	3.61	0.75	45.63	126.88	10.0	3.33	0.69	0.1	78.1
M-4	static mixer	1.33	20.1	0.60	0.0	4.81	1.00	49.12	128.53	12.1	4.43	0.92	0.1	92.1
M-5	static mixer	1.33	20.1	0.60	0.0	7.21	1.50	51.87	129.87	13.6	6.63	1.38	0.1	101.0
M-6	static mixer	1.33	20.1	0.60	0.0	9.62	2.00	54.24	130.71	15.3	8.83	1.84	0.1	109.7
M-7	static mixer	1.33	20.1	0.60	0.0	12.02	2.50	56.77	131.55	17.2	11.02	2.29	0.1	118.9
M-8	static mixer	1.33	20.1	0.60	0.0	14.43	3.00	58.29	131.57	18.8	13.22	2.75	0.1	126.3
N-1	static mixer	1.2	30	0.90	0.0	1.21	0.25	39.88	125.19	5.5	1.12	0.23	0.0	43.4
N-2	static mixer	1.2	30.1	0.90	0.0	2.41	0.50	51.01	131.61	10.7	2.21	0.46	0.0	80.6
N-3	static mixer	1.2	30	0.90	0.0	3.75	0.78	58.16	134.81	15.1	3.43	0.71	0.0	109.6
N-4	static mixer	1.2	30	0.90	0.0	4.81	1.00	60.15	134.66	17.5	4.40	0.91	0.0	124.6
O-1	static mixer	1.17	39	1.17	0.0	1.21	0.25	44.49	128.31	7.2	1.12	0.23	0.0	53.2
O-2	static mixer	1.17	37	1.11	0.0	2.41	0.50	57.44	135.04	14.1	2.20	0.46	0.0	97.5
O-3	static mixer	1.17	37	1.11	0.0	3.61	0.75	62.03	136.03	18.1	3.29	0.69	0.0	122.9
V-1	0.5 micron S.S.	1.26	n/a	n/a	0.0	1.21	0.25	34.91	122.21	3.3	1.12	0.23	0.1	27.6
V-2	0.5 micron S.S.	1.26	n/a	n/a	0.0	2.41	0.50	37.98	123.96	4.8	2.23	0.46	0.1	38.9
V-3	0.5 micron S.S.	1.26	n/a	n/a	0.0	3.61	0.75	41.28	125.42	6.8	3.34	0.70	0.1	54.2
V-4	0.5 micron S.S.	1.26	n/a	n/a	0.0	4.81	1.00	44.19	126.7	8.6	4.44	0.92	0.1	67.0
V-5	0.5 micron S.S.	1.26	n/a	n/a	0.0	7.21	1.50	48.78	128.65	11.6	6.64	1.38	0.1	86.1
V-6	0.5 micron S.S.	1.26	n/a	n/a	0.0	9.62	2.00	51.71	129.97	13.3	8.84	1.84	0.1	95.8
V-7	0.5 micron S.S.	1.26	n/a	n/a	0.0	12.02	2.50	54.32	130.74	15.4	11.03	2.30	0.1	106.8
V-8	0.5 micron S.S.	1.26	n/a	n/a	0.0	14.42	3.00	56.73	131.33	17.4	13.22	2.75	0.2	117.0

B-1 Test conditions (Porous Sparger)

Test Series	Test Objectives	Superficial Flow Rates (cm/s)				Bias (cm/s)	Air Flow (cm/s, STP)	Height (cm)	Level (cm)	Residence Time (min)	P2 (cm H_2O)	P3 (cm H_2O)	E_g (%)	Corr. J_g (cm/s, P2-P3)	d_b(P2-P3) (cm)	S_b(P2-P3) (s^{-1})
		Feed	Washwater	Accepts	Rejects											
ISP-9	residence/air	1.04	0.17	1.18	0.02	0.14	1.5	465	65	5.0	205.7	285.8	11.0	1.21	0.11	68.2
ISP-10	residence time	2.29	0.17	2.43	0.02	0.14	1.5	465	65	2.4	204.0	283.1	12.0	1.21	0.11	64.4
ISP-11	residence time	0.23	0.17	0.35	0.02	0.12	1.5	465	65	16.9	205.7	286.6	10.0	1.20	0.11	68.1
ISP-12	residence time	1.71	0.17	1.81	0.07	0.10	1.5	465	65	3.1	196.7	272.3	16.1	1.22	0.09	83.5
ISP-13	air rate	1.04	0.17	1.19	0.02	0.14	1	465	65	5.1	203.7	285.4	9.2	0.81	0.08	57.5
ISP-14	air rate	1.04	0.17	1.19	0.01	0.15	0.75	465	65	5.3	205.5	289.8	6.3	0.60	0.09	41.3
ISP-15	air rate	1.04	0.17	1.19	0.02	0.15	2	465	65	5.0	197.5	277.5	11.1	1.62	0.14	68.0
ISP-16	air rate	1.04	0.17	1.17	0.04	0.12	2.5	465	65	4.8	189.3	265.1	15.7	2.05	0.13	91.5
ISP-17	air rate	1.02	0.17	1.17	0.02	0.15	1.5	465	65	5.2	202.2	283.6	9.5	1.21	0.12	59.8
ISP-18	residence time	0.52	0.17	0.64	0.02	0.12	1.5	465	65	9.3	199.9	280.0	11.0	1.22	0.10	71.9
ISP-19	residence time	1.67	0.17	1.80	0.02	0.13	1.5	465	65	3.3	200.3	280.6	10.8	1.22	0.12	62.9
ISP-20	air rate	1.07	0.17	1.17	0.02	0.10	2	465	65	5.0	196.3	275.4	13.0	1.62	0.12	78.1
ISP-21	air rate	1.00	0.17	1.02	0.14	0.02	3	465	65	5.1	179.6	250.0	22.6	2.50	0.12	121.4
ISP-22	air rate	1.01	0.17	1.01	0.15	0.00	2.5	465	65	5.2	184.2	256.0	21.0	2.08	0.11	115.6
ISP-23	residence/air	1.05	0.17	1.18	0.02	0.13	1.5	465	65	5.0	202.3	283.5	10.7	1.23	0.11	66.3
ISP-24	minimum air	1.05	0.17	1.20	0.00	0.15	0.5	465	65	5.4	213.7	302.6	2.3	0.40	0.16	15.0
ISP-25	minimum air	1.05	0.17	1.20	0.00	0.15	0.6	465	65	5.4	213.2	302.0	2.4	0.48	0.18	15.8
ISP-26	minimum air	1.04	0.17	1.20	0.00	0.16	0.7	465	65	5.4	212.7	301.1	2.7	0.57	0.19	17.8
ISP-27	residence time	1.69	0.17	1.78	0.08	0.09	1.5	465	65	3.2	196.2	273.1	15.4	1.22	0.09	81.7
ISP-28	residence time	1.95	0.17	2.06	0.06	0.11	1.5	465	65	2.7	195.8	273.1	15.0	1.24	0.10	77.8
ISP-29	residence time	0.16	0.17	0.26	0.04	0.10	1.5	465	65	22.3	201.9	280.2	13.8	1.23	0.08	91.9
ISP-30	froth depth	1.05	0.17	1.18	0.05	0.12	1.5	465	120	4.2	149.5	227.3	14.3	1.28	0.09	84.3
ISP-31	froth depth	1.05	0.17	1.17	0.04	0.12	1.5	465	90	4.6	176.5	254.4	14.3	1.26	0.09	84.2
ISP-32	froth depth	1.04	0.17	1.17	0.03	0.13	1.5	465	35	5.4	222.4	302.4	12.0	1.21	0.10	73.2
ISP-33	froth depth	1.06	0.17	1.17	0.07	0.11	1.5	465	10	5.8	241.8	322.6	11.1	1.19	0.10	68.8
ISP-34	wash water	1.08	0.00	1.07	0.00	-0.01	1.5	465	65	5.6	196.2	277.3	9.8	1.23	0.12	62.2
ISP-35	wash water	1.11	0.08	1.18	0.01	0.07	1.5	465	65	5.1	198.7	279.7	9.9	1.23	0.12	62.1
ISP-36	wash water	1.05	0.27	1.29	0.02	0.25	1.5	465	65	4.6	202.8	283.6	10.1	1.23	0.12	62.4
ISP-37	wash water	1.08	0.03	1.10	0.01	0.02	1.5	465	65	5.5	200.2	282.3	8.7	1.23	0.13	55.1
ISP-38	residence time	0.65	0.17	0.78	0.02	0.14	1.5	465	65	7.7	200.4	281.5	9.7	1.23	0.12	63.1
ISP-39	residence time	0.34	0.17	0.49	0.01	0.15	1.5	465	65	12.3	201.9	283.5	9.3	1.23	0.12	61.9
ISP-40	air rate	1.06	0.17	1.20	0.03	0.14	2	465	65	5.0	200.0	280.5	10.4	1.64	0.15	63.9
ISP-41	air rate	1.05	0.17	1.14	0.06	0.09	3	465	65	4.9	189.8	264.9	16.5	2.49	0.16	94.2
ISP-42	air rate	1.05	0.17	1.20	0.00	0.15	1	465	65	5.2	209.7	294.5	5.8	0.81	0.13	37.5
ISP-43	air rate	1.04	0.17	1.19	0.01	0.15	0.75	465	65	5.3	211.7	296.5	5.7	0.61	0.10	37.7
ISP-44	wash water	1.04	0.01	1.05	0.01	0.01	1.5	465	65	5.7	200.6	281.5	10.1	1.23	0.12	63.7
ISP-45	air rate	1.03	0.17	1.19	0.01	0.16	1	465	65	5.2	210.4	294.4	6.6	0.81	0.11	43.1
ISP-46	column height	1.03	0.17	1.14	0.05	0.11	1.5	310	65	2.9	39.0	112.3	19.0	1.41	0.08	103.5
ISP-47	column height	0.27	0.17	0.37	0.05	0.10	1.5	310	65	9.0	39.1	112.6	18.8	1.41	0.07	115.7
ISP-48	column height	2.10	0.17	2.21	0.04	0.11	1.5	310	65	1.5	40.0	115.6	16.5	1.41	0.10	82.7
ISP-49	column height	1.52	0.17	1.63	0.05	0.11	1.5	310	65	2.0	38.3	109.8	21.0	1.42	0.08	101.5
ISP-50	column height	0.58	0.17	0.69	0.04	0.11	1.5	310	65	4.8	39.0	112.5	18.9	1.41	0.08	110.1
ISP-52*	long term	0.62	0.17	0.69	0.07	0.08	2.5	310	65	4.7	38.9	112.0	19.3	2.36	0.13	112.2

* Average values

B-2 Flotation efficiency and brightness gain results (Porous Sparger)

Test	Brightness (ISO)			Column	Plant	ERIC (ppm)			Column	Plant
Series	Feed	Accepts	Plant	Gain	Gain	Feed	Accepts	Plant	Efficiency (%)	Efficiency (%)
ISP-9	44.59	56.14	56.45	11.55	11.86	1005.9	301.9	232.9	70.0	76.8
ISP-10	45.77	52.85	56.98	7.08	11.21	939.9	452.4	232.8	51.9	75.2
ISP-11	46.1	58.82	57.42	12.72	11.32	906.1	180.4	235	80.1	74.1
ISP-12	46.58	57.25	58.04	10.67	11.46	917.4	263.4	217.4	71.3	76.3
ISP-13	46.4	55.89	55.94	9.49	9.54	884.1	263.3	227	70.2	74.3
ISP-14	46.03	54.72	57.38	8.69	11.35	883.7	335.7	214.6	62.0	75.7
ISP-15	45.27	54.86	55.79	9.59	10.52	919.6	253.9	216.4	72.4	76.5
ISP-16	45.32	56.76	57.5	11.44	12.18	918.9	213.5	203.7	76.8	77.8
ISP-17	46.52	57.2	58.64	10.68	12.12	922.6	261.3	196.6	71.7	78.7
ISP-18	46.03	58.32	58.66	12.29	12.63	946.3	189.3	204.4	80.0	78.4
ISP-19	45.68	55.33	58.78	9.65	13.10	942.5	316.4	187.7	66.4	80.1
ISP-20	46.04	57.39	57.01	11.35	10.97	920.8	223.41	232.85	75.7	74.7
ISP-21	47.39	58.11	57.34	10.72	9.95	845.02	171.31	229.2	79.7	72.9
ISP-22	47.28	58.39	57.65	11.11	10.37	878.72	184.39	230.6	79.0	73.8
ISP-23	48.08	58.19	59.24	10.11	11.16	785.33	229.75	187.25	70.7	76.2
ISP-24	n/a	n/a	n/a	0.00	n/a	n/a	n/a	n/a	0.00	n/a
ISP-25	n/a	n/a	n/a	0.00	n/a	n/a	n/a	n/a	0.00	n/a
ISP-26	n/a	n/a	n/a	0.00	n/a	n/a	n/a	n/a	0.00	n/a
ISP-27	45.16	55.61	56.4	10.45	11.24	1018.11	342.74	309.73	66.3	69.6
ISP-28	45.45	54.58	56.48	9.13	11.03	981.98	331.7	281.8	66.2	71.3
ISP-29	45.35	58.02	57	12.67	11.65	1001.5	214.01	279.6	78.6	72.1
ISP-30	47.81	58.15	57.77	10.34	9.96	930.99	238.66	214.68	74.4	76.9
ISP-31	48.54	57.82	58.02	9.28	9.48	790.7	200.9	189.9	74.6	76.0
ISP-32	46.66	57.55	58.21	10.89	11.55	935.7	241.3	197	74.2	78.9
ISP-33	47.95	57.48	57.14	9.53	9.19	816.6	243.1	189.4	70.2	76.8
ISP-34	48.85	57.91	60.71	9.06	11.86	822.66	275.6	151.3	66.5	81.6
ISP-35	49.18	58.2	61.06	9.02	11.88	804.52	273.47	153.9	66.0	80.9
ISP-36	48.2	57.55	60.55	9.35	12.35	879.62	303.06	166.08	65.5	81.1
ISP-37	48.19	56.71	60.17	8.52	11.98	830.25	281.3	167.6	66.1	79.8
ISP-38	47.28	56.54	58.05	9.26	10.77	788.88	251.7	203.81	68.1	74.2
ISP-39	47.97	57.38	58.07	9.41	10.10	819.99	221.91	219.79	72.9	73.2
ISP-40	48.46	56.9	59.96	8.44	11.50	795.5	302.11	183.64	62.0	76.9
ISP-41	48.83	59.93	60.39	11.10	11.56	786.72	196.35	178.7	75.0	77.3
ISP-42	46.57	55.31	58.51	8.74	11.94	911.5	359.7	214.7	60.5	76.4
ISP-43	46.3	53.11	57.94	6.81	11.64	811.67	415.79	213.68	48.8	73.7
ISP-44	48.88	58.48	59.68	9.60	10.80	750.53	282.8	214.1	62.3	71.5
ISP-45	46.23	53.09	57.11	6.86	10.88	823.4	446.9	245.14	45.7	70.2
ISP-46	45.07	56.49	57.39	11.42	12.32	1105.8	318.5	283.2	71.2	74.4
ISP-47	45.37	57.97	57.79	12.60	12.42	1048.3	231.4	263	77.9	74.9
ISP-48	45.22	54.24	57.41	9.02	12.19	1058.9	431	284.7	59.3	73.1
ISP-49	46.5	57.56	58.7	11.06	12.20	947.1	277.4	240.3	70.7	74.6
ISP-50	47.69	59.59	60.03	11.90	12.34	889.9	196.6	218.6	77.9	75.4
ISP-52*	46.94	57.2	59.05	10.26	12.11	909	249.6	191.3	72.5	79.0

* Average values

B-3 Flow rate, consistency, organic content, and standard deviation data (Porous Sparger)

Test	Mean Flow Rates (l/min)				Flow Rates-Std Dev. (l/min)				Mean Consistency (%)			Consistency Std Dev. (%)*			Organics (%)			Organics Std Dev. (%)*		
Series	Feed	Wash Water	Accepts	Rejects	Feed	Wash Water*	Accepts	Rejects*	Feed	Accepts	Rejects	Feed	Accepts	Rejects	Feed	Accepts	Rejects	Feed	Accepts	Rejects
ISP-9	4.98	0.82	5.66	0.099	0.08	0.1	0.31	0.1	1.38	1.14	0.65	0.02	0.01	0.25	88.81	89.68	55.39	0.36	0.32	2.21
ISP-10	11.01	0.83	11.7	0.116	0.22	0.1	0.25	0.1	1.39	1.32	1.28	0.02	0.01	0.25	86.34	87.34	56.77	0.36	0.32	2.21
ISP-11	1.1	0.83	1.7	0.115	0.13	0.1	0.48	0.1	1.3	0.78	0.79	0.02	0.01	0.25	86.57	89.94	52.41	0.36	0.32	2.21
ISP-12	8.24	0.83	8.7	0.328	0.05	0.1	0.40	0.1	1.26	1.16	1.48	0.02	0.01	0.25	86.97	89.19	49.7	0.36	0.32	2.21
ISP-13	5.01	0.82	5.7	0.076	0.07	0.1	0.27	0.1	1.25	1.11	0.73	0.02	0.01	0.25	86.22	89.86	56.77	0.36	0.32	2.21
ISP-14	5	0.82	5.7	0.047	0.07	0.1	0.21	0.1	1.27	1.11	1.07	0.02	0.01	0.25	87.5	89.06	60.79	0.36	0.32	2.21
ISP-15	5	0.82	5.7	0.089	0.07	0.1	0.28	0.1	1.27	1.1	0.5	0.02	0.01	0.25	87.51	90.14	56.05	0.36	0.32	2.21
ISP-16	5	0.83	5.6	0.2	0.11	0.1	0.33	0.1	1.22	1.09	0.86	0.02	0.01	0.25	87.05	90.61	54.37	0.36	0.32	2.21
ISP-17	4.9	0.82	5.6	0.074	0.06	0.1	0.27	0.1	1.12	1.01	0.96	0.02	0.01	0.25	86.53	90.55	53.88	0.36	0.32	2.21
ISP-18	2.5	0.83	3.06	0.098	0.11	0.1	0.57	0.1	1.17	0.99	0.79	0.02	0.01	0.25	85.94	88.11	56.41	0.36	0.32	2.21
ISP-19	8.04	0.83	8.67	0.112	0.06	0.1	0.21	0.1	1.29	1.13	2.27	0.02	0.01	0.25	84.6	89.92	58.03	0.36	0.32	2.21
ISP-20	5.12	0.83	5.62	0.118	0.09	0.1	0.23	0.1	1.21	1.08	0.96	0.02	0.01	0.25	86.94	90.51	64.99	0.36	0.32	2.21
ISP-21	4.8	0.83	4.9	0.688	0.07	0.1	0.59	0.1	1.17	1.05	0.56	0.02	0.01	0.25	88.03	91.35	52.5	0.36	0.32	2.21
ISP-22	4.84	0.83	4.85	0.736	0.08	0.1	0.60	0.1	1.22	1.1	0.53	0.02	0.01	0.25	89.94	91.39	61.19	0.36	0.32	2.21
ISP-23	5.04	0.83	5.68	0.109	0.04	0.1	0.27	0.1	1.17	0.95	1.21	0.02	0.01	0.25	85.22	89.32	64.9	0.36	0.32	2.21
ISP-24	5.06	0.83	5.76	0	n/a	0.1	n/a	0.1	n/a	n/a	n/a	0.02	0.01	0.25	n/a	n/a	n/a	0.36	0.32	2.21
ISP-25	5.03	0.83	5.77	0	n/a	0.1	n/a	0.1	n/a	n/a	n/a	0.02	0.01	0.25	n/a	n/a	n/a	0.36	0.32	2.21
ISP-26	5.02	0.83	5.77	0	n/a	0.1	n/a	0.1	n/a	n/a	n/a	0.02	0.01	0.25	n/a	n/a	n/a	0.36	0.32	2.21
ISP-27	8.13	0.83	8.54	0.378	0.14	0.1	0.48	0.1	1.17	1.07	1.29	0.02	0.01	0.25	86.96	90.11	61.39	0.36	0.32	2.21
ISP-28	9.39	0.83	9.9	0.286	0.08	0.1	0.24	0.1	1.12	0.99	1.59	0.02	0.01	0.25	88.26	93.15	62.79	0.36	0.32	2.21
ISP-29	0.76	0.83	1.24	0.202	0.06	0.1	0.55	0.1	1.14	0.6	0.22	0.02	0.01	0.25	88.82	91.52	55.06	0.36	0.32	2.21
ISP-30	5.07	0.83	5.66	0.237	0.13	0.1	0.31	0.1	1.13	1	1.25	0.02	0.01	0.25	88.83	91.91	48.84	0.36	0.32	2.21
ISP-31	5.04	0.83	5.62	0.176	0.05	0.1	0.30	0.1	1.13	0.98	1.19	0.02	0.01	0.25	86.96	91.45	54.25	0.36	0.32	2.21
ISP-32	5.01	0.83	5.63	0.158	0.07	0.1	0.38	0.1	1.28	1.12	1.5	0.02	0.01	0.25	87.75	90.76	59.1	0.36	0.32	2.21
ISP-33	5.1	0.83	5.61	0.336	0.06	0.1	0.45	0.1	1.33	1.2	1.11	0.02	0.01	0.25	87.37	89.83	52.48	0.36	0.32	2.21
ISP-34	5.17	0	5.14	0.004	0.05	0	0.27	0.1	1.2	1.17	14.4	0.02	0.01	0.25	87.57	89.57	54.83	0.36	0.32	2.21
ISP-35	5.33	0.4	5.65	0.068	0.03	0.1	0.29	0.1	1.22	1.07	4.3	0.02	0.01	0.25	88.3	89.73	51.03	0.36	0.32	2.21
ISP-36	5.03	1.3	6.22	0.085	0.04	0.1	0.24	0.1	1.22	0.95	0.43	0.02	0.01	0.25	86.41	89.5	53.85	0.36	0.32	2.21
ISP-37	5.21	0.15	5.3	0.025	0.03	0.1	0.39	0.1	1.23	1.16	6	0.02	0.01	0.25	89.12	91.38	54.97	0.36	0.32	2.21
ISP-38	3.1	0.83	3.76	0.12	0.57	0.1	0.70	0.1	1.2	0.93	0.48	0.02	0.01	0.25	89.36	91.49	57.78	0.36	0.32	2.21
ISP-39	1.65	0.83	2.36	0.043	0.05	0.1	0.34	0.1	1.2	0.79	1.27	0.02	0.01	0.25	89.36	91.49	57.78	0.36	0.32	2.21
ISP-40	5.09	0.83	5.75	0.135	0.05	0.1	0.29	0.1	1.25	1.07	0.35	0.02	0.01	0.25	87.06	88.74	56.68	0.36	0.32	2.21
ISP-41	5.06	0.81	5.49	0.292	0.14	0.1	0.37	0.1	1.25	1.06	1.4	0.02	0.01	0.25	87.19	90.13	45.93	0.36	0.32	2.21
ISP-42	5.05	0.82	5.78	0.022	0.06	0.1	0.24	0.1	1.27	1.07	0.52	0.02	0.01	0.25	86.6	89.25	49.2	0.36	0.32	2.21
ISP-43	4.96	0.82	5.71	0.04	0.14	0.1	0.24	0.1	1.23	0.98	1.66	0.02	0.01	0.25	83.7	87.02	45.18	0.36	0.32	2.21
ISP-44	4.99	0.15	5.04	0.048	0.05	0.1	0.38	0.1	1.3	1.16	0.96	0.02	0.01	0.25	83.58	87.56	43.32	0.36	0.32	2.21
ISP-45	4.96	0.82	5.71	0.05	1.22	0.1	0.26	0.1	1.31	1.08	4.07	0.02	0.01	0.25	84.51	87.04	44.82	0.36	0.32	2.21
ISP-46	4.96	0.81	5.48	0.223	0.06	0.1	0.29	0.1	1.25	1.08	1.77	0.02	0.01	0.25	86.79	90.95	50.59	0.36	0.32	2.21
ISP-47	1.29	0.81	1.77	0.228	0.14	0.1	0.39	0.1	1.24	0.79	0.67	0.02	0.01	0.25	86.87	91.94	50.48	0.36	0.32	2.21
ISP-48	10.08	0.81	10.62	0.194	0.08	0.1	0.22	0.1	1.22	1.13	2.43	0.02	0.01	0.25	88.18	90.21	55.7	0.36	0.32	2.21
ISP-49	7.31	0.81	7.84	0.232	0.14	0.1	0.22	0.1	1.2	1.12	2.19	0.02	0.01	0.25	88.13	90.3	55.31	0.36	0.32	2.21
ISP-50	2.79	0.81	3.33	0.207	0.43	0.1	0.47	0.1	1.21	0.92	1.31	0.02	0.01	0.25	86.26	90.98	52.37	0.36	0.32	2.21
ISP-52**	2.96	0.81	3.34	0.336	0.22	0.1	0.49	0.1	1.21	1.02	0.76	0.02	0.01	0.25	87.97	90.99	55.53	0.36	0.32	2.21

* Calculated from experimental error test ** Average values

B-4 Material balanced data (Porous Sparger)

Test	Feed				Accepts				Rejects				Wash Water	Reject Rate	Ash Loss	Ink Recovery	Organic Loss
Series	(ml/min)	% Solids	% Organic	% Ash	(ml/min)	% Solids	% Organic	% Ash	(ml/min)	% Solids	% Organic	% Ash	(ml/min)	(%)	(%)	(%)	(%)
ISP-9	4955.5	1.34	89.03	10.97	5680.2	1.15	89.51	10.49	97.9	0.94	55.27	44.73	822.5	2.0	5.7	70.5	0.9
ISP-10	10973.5	1.41	86.86	13.14	11685.9	1.32	86.98	13.02	117	0.54	56.69	43.31	829.4	1.1	1.3	52.0	0.3
ISP-11	1230.1	1.32	86.86	13.14	1917.8	0.77	89.73	10.27	119.4	1.02	51.60	48.40	827.1	9.7	27.6	81.7	4.5
ISP-12	8233.3	1.28	87.14	12.87	8732.4	1.15	89.07	10.93	329.7	1.56	49.40	50.60	828.8	4.0	19.2	72.6	2.8
ISP-13	4994.3	1.28	87.96	12.04	5731.2	1.1	88.51	11.49	80.9	1.34	55.67	44.33	817.8	1.6	6.2	70.6	1.1
ISP-14	5009	1.29	88.22	11.79	5775.6	1.11	88.50	11.50	52.4	1.26	60.51	39.49	819	1.0	3.4	62.3	0.7
ISP-15	4988	1.28	88.69	11.31	5716.1	1.1	89.22	10.78	91	1.09	55.36	44.64	819.1	1.8	6.1	72.8	1.0
ISP-16	5039.2	1.26	88.39	11.61	5662.8	1.08	89.83	10.17	203.8	1.33	55.86	44.14	827.5	4.0	16.2	77.6	2.7
ISP-17	4907.6	1.17	88.61	11.40	5643.9	1	89.41	10.59	81.1	1.57	53.07	46.93	817.3	1.7	9.1	72.2	1.3
ISP-18	2579.8	1.29	87.75	12.25	3290.4	0.96	89.63	10.37	109.8	1.5	51.60	48.40	820.4	4.3	19.6	81.0	2.9
ISP-19	8013.5	1.27	86.63	13.37	8725.1	1.13	87.58	12.42	118.5	2.55	55.64	44.36	830.2	1.5	9.9	67.5	1.9
ISP-20	5029.9	1.26	86.81	13.19	5731.2	1.06	88.25	11.75	124.8	2.16	54.49	45.51	826.1	2.5	14.7	76.7	2.7
ISP-21	4738.4	1.2	87.31	12.69	4874.6	1.04	90.25	9.75	691	0.9	63.45	36.55	827.2	14.6	31.5	81.9	7.9
ISP-22	4787.6	1.22	88.12	11.88	4881.4	1.1	91.28	8.72	736.1	0.64	52.22	47.78	830	15.4	32.4	80.7	4.8
ISP-23	5022	1.13	90.15	9.85	5740.5	0.96	91.23	8.77	112.6	1.81	60.91	39.09	831	2.2	14.2	71.6	2.4
ISP-24	5060	n/a	n/a	n/a	5760	n/a	n/a	n/a	n/a	n/a	n/a	n/a	831.4	n/a	n/a	n/a	n/a
ISP-25	5030	n/a	n/a	n/a	5770	n/a	n/a	n/a	n/a	n/a	n/a	n/a	829	n/a	n/a	n/a	n/a
ISP-26	5020	n/a	n/a	n/a	5770	n/a	n/a	n/a	n/a	n/a	n/a	n/a	828.4	n/a	n/a	n/a	n/a
ISP-27	8111.6	1.21	86.36	13.64	8559	1.06	88.49	11.51	381.1	2.04	61.51	38.49	828.5	4.7	22.3	68.9	5.6
ISP-28	9357.8	1.11	87.75	12.25	9898.7	0.99	89.53	10.47	288.9	2.14	59.63	40.37	829.8	3.1	19.6	68.1	4.0
ISP-29	863.4	1.17	88.58	11.42	1480.3	0.59	92.93	7.07	207.6	0.66	61.15	38.85	824.5	24.0	46.1	81.5	9.4
ISP-30	5102.7	1.17	89.17	10.83	5690.9	0.99	91.26	8.74	239.9	1.4	54.31	45.69	828.1	4.7	23.7	75.8	2.4
ISP-31	5023.9	1.17	89.30	10.70	5669.7	0.99	89.30	10.70	181.4	1.68	47.92	52.08	827.2	3.6	25.2	75.7	2.8
ISP-32	5001.5	1.33	88.18	11.82	5662	1.1	90.55	9.46	166.3	2.42	51.47	48.53	826.8	3.3	24.8	75.9	3.5
ISP-33	5071.3	1.38	88.37	11.63	5557.7	1.18	90.30	9.70	140	1.22	57.72	42.28	826.4	6.7	21.5	72.1	3.9
ISP-34	5160.4	1.2	87.47	12.53	5133.5	1.2	89.76	10.24	27	14.4	52.26	47.74	0	0.5	23.9	66.7	3.8
ISP-35	5323.2	1.2	87.97	12.04	5651.5	1.07	89.58	10.42	72.5	4.09	54.86	45.14	400.8	1.4	17.4	67.8	2.9
ISP-36	5016.4	1.2	88.88	11.12	6231.4	0.95	89.28	10.72	85.4	0.73	50.80	49.20	1300.4	1.7	4.6	66.1	0.6
ISP-37	5202.1	1.24	87.04	12.96	5294	1.15	89.03	10.97	56.7	6.19	52.55	47.45	148.6	1.1	19.9	68.0	3.3
ISP-38	2720.2	1.21	89.57	10.44	3426.4	0.92	91.04	8.96	122.3	1.08	54.30	45.70	828.5	4.5	17.6	69.4	2.4
ISP-39	1657.3	1.21	89.74	10.26	2433.6	0.79	91.21	8.80	52.6	1.64	57.17	42.83	828.9	3.2	18.0	74.1	2.7
ISP-40	5076.4	1.24	87.68	12.32	5771.3	1.07	88.26	11.74	135.3	0.84	56.26	43.74	830.1	2.7	6.4	62.7	1.2
ISP-41	5061	1.25	87.24	12.77	5579	1.06	90.10	9.90	292	1.4	45.82	54.18	810	5.8	27.4	76.7	3.4
ISP-42	5026.5	1.25	88.03	11.97	5822.9	1.07	88.13	11.87	24.3	0.66	49.06	50.94	820.8	0.5	1.1	60.9	0.1
ISP-43	4937	1.18	85.06	14.94	5705.3	0.99	85.97	14.03	54.2	2.33	44.07	55.93	822.5	1.1	8.1	50.3	1.1
ISP-44	4938	1.22	85.42	14.58	5038.9	1.18	86.13	13.87	53	1.84	42.20	57.80	153.9	1.1	6.4	62.8	2.8
ISP-45	4939.7	1.3	84.91	15.09	5694.9	1.3	84.91	15.09	65.1	4.24	44.17	55.83	820.3	1.3	15.9	37.4	2.2
ISP-46	4953.6	1.29	87.30	12.70	5531.7	1.07	90.58	9.42	229.2	2.2	49.06	50.94	807.3	4.6	31.7	73.3	4.4
ISP-47	1349.8	1.25	87.89	12.11	1929.3	0.79	87.89	12.11	229.4	0.71	50.41	49.59	808.8	17.0	39.5	80.1	5.5
ISP-48	10068.5	1.24	88.53	11.47	10680.1	1.12	89.95	10.05	197.5	2.59	55.17	44.83	809.2	2.0	1.6	61.0	0.3
ISP-49	7301.3	1.26	88.29	11.71	7875.9	1.1	90.18	9.82	233.2	2.12	54.99	45.01	807.7	3.2	20.7	72.4	3.3
ISP-50	2808.3	1.24	86.54	13.46	3403.5	0.91	90.78	9.22	212.1	1.76	51.25	48.76	819	7.6	38.8	80.4	6.3
ISP-52*	2959.13	1.26	87.36	12.64	3553.9	0.99	89.39	10.61	211.4	0.91	53.86	46.14	808.2	7.2	19.0	74.1	3.2

* Average values

C-1 Test conditions (Static Mixer Sparger)

Test Series	Test Objectives	Flowrates (cm/s)				Sparger Pulp Rate (m/s)	Bias (cm/s)	Air Flow (cm/s, STP)	Height (cm)	Residence Time (min)	Froth Depth (cm)	P2 (cm H2O)	P3 (cm H2O)	ε_g (%)	Corr. J_g (cm/s, P2-P3)	d_b (P2-P3) d_b	S_b (P2-P3) (s^{-1})
		Feed	Washwater	Accepts	Rejects												
MIV-1	air rate and 20 l/min	1.05	0.17	1.21	0.01	0.6	0.16	1	465	5.0	65	204.48	287.16	9.4	0.81	0.08	58.6
MIV-2	air rate and 20 l/min	1.05	0.17	1.21	0.02	0.6	0.16	2	465	4.9	65	199.42	280.44	11.3	1.62	0.14	68.6
MIV-3	air rate and 20 l/min	1.05	0.17	1.21	0.02	0.6	0.16	2.5	465	4.8	65	197.54	277.7	12.2	2.03	0.17	72.7
MIV-4	air rate and 20 l/min	1.04	0.17	1.20	0.02	0.6	0.16	1.5	465	5.0	65	201.84	283.35	10.4	1.21	0.11	64.7
MIV-5	air rate and 20 l/min	1.04	0.17	1.21	0.01	0.6	0.16	0.75	465	5.1	65	207.61	292.5	6.7	0.60	0.08	43.3
MIV-6	air rate and 30 l/min	1.06	0.17	1.22	0.01	0.9	0.16	1	465	4.7	65	194.31	273.09	13.4	0.82	0.06	75.8
MIV-7	air rate and 30 l/min	1.04	0.17	1.17	0.06	0.9	0.12	2	465	4.6	65	184.97	257.80	20.0	1.65	0.09	107.9
MIV-8	air rate and 30 l/min	1.05	0.17	1.23	0.01	0.9	0.19	0.5	465	5.1	65	209.35	294.48	6.5	0.40	0.06	40.0
MIV-9	air rate and 30 l/min	1.05	0.17	1.21	0.04	0.9	0.16	2.5	465	4.6	65	189.26	265.37	16.4	2.05	0.13	93.9
MIV-10	rtd and 20 l/min	1.07	0.17	1.23	0.03	0.6	0.16	1.5	465	4.7	65	196.35	274.96	13.6	1.24	0.09	80.3
MIV-11	rtd and 20 l/min	2.23	0.17	2.41	0.03	0.6	0.18	1.5	465	2.4	65	199.02	278.73	11.6	1.23	0.12	62.9
MIV-12	rtd and 20 l/min	0.25	0.17	0.40	0.03	0.6	0.15	1.5	465	14.5	65	194.69	272.93	13.3	1.24	0.09	87.1
MIV-13	rtd and 20 l/min	0.65	0.17	0.81	0.02	0.6	0.16	1.5	465	7.2	65	196.77	276.37	11.8	1.24	0.10	74.7
MIV-14	rtd and 20 l/min	1.63	0.17	1.81	0.02	0.6	0.17	1.5	465	3.3	65	202.09	283.24	10.0	1.23	0.13	59.2
MIV-15	rtd and 30 l/min	1.06	0.17	1.24	0.03	0.9	0.17	1.5	465	4.6	65	192.65	269.29	15.0	1.24	0.09	86.3
MIV-16	rtd and 30 l/min	2.21	0.17	2.42	0.04	0.9	0.21	1.5	465	2.4	65	196.60	275.12	12.9	1.24	0.11	67.9
MIV-17	rtd and 30 l/min	0.24	0.17	0.39	0.05	0.9	0.16	1.5	465	14.0	65	189.46	263.81	17.6	1.25	0.07	108.9
MIV-18	rtd and 30 l/min	1.60	0.17	1.85	0.02	0.9	0.24	1.5	465	3.2	65	198.44	277.40	12.5	1.23	0.11	70.1
MIV-19	rtd and 30 l/min	0.57	0.17	0.74	0.04	0.9	0.17	1.5	465	7.6	65	191.60	267.14	16.3	1.24	0.08	97.7
MIV-20	recycle 15 l/min	1.07	0.17	1.22	0.01	0.5	0.15	1.5	465	5.1	65	203.89	287.00	7.0	1.23	0.17	44.4
MIV-21	recycle 25 l/min	1.07	0.17	1.24	0.02	0.8	0.17	1.5	465	4.8	65	194.38	273.18	11.9	1.24	0.10	72.0
MIV-22	recycle 35 l/min	1.05	0.17	1.20	0.04	1.1	0.15	1.5	465	4.8	65	191.71	268.94	13.6	1.24	0.09	80.7
MIV-23	recycle 20 l/min	1.04	0.17	1.19	0.02	0.6	0.15	1.5	465	5.1	65	200.14	281.32	9.2	1.23	0.13	57.7
MIV-24	recycle 30 l/min	1.04	0.17	1.20	0.04	0.9	0.15	1.5	465	4.8	65	191.77	268.82	13.8	1.24	0.09	81.6
MIV-25	recycle 10 l/min	1.04	0.17	1.18	0.00	0.3	0.15	1.5	465	5.4	65	207.34	292.57	4.7	1.22	0.26	28.6
MIV-26	recycle 5 l/min	1.04	0.17	1.18	n/a	0.2	0.14	1.5	465	5.4	65	207.09	293.19	3.7	1.22	0.33	21.9
MIV-27	recycle 10 l/min	1.05	0.17	1.19	0.01	0.3	0.14	2.5	465	5.2	65	203.25	285.97	7.5	2.05	0.28	44.1
MIV-28	recycle 20 l/min	1.06	0.17	1.22	0.02	0.6	0.16	2.5	465	4.8	65	194.63	273.09	12.2	2.06	0.17	72.7
MIV-29	recycle 30 l/min	1.07	0.17	1.22	0.05	0.9	0.15	2.5	465	4.6	65	185.49	259.68	17.0	2.08	0.13	96.7
MIV-30	recycle 33 l/min	1.07	0.17	1.20	0.07	1.0	0.14	2.5	465	4.4	65	179.97	251.4	20.1	2.09	0.11	109.5
MIV-31	recycle 5 l/min	1.07	0.17	1.20	0.01	0.2	0.14	2.5	465	5.2	65	204.87	288.27	6.7	2.04	0.31	39.2
MIV-32	recycle 15 l/min	1.07	0.17	1.20	0.02	0.4	0.14	2.5	465	5.0	65	200.6	282.2	8.7	2.05	0.24	52.0
MIV-33	recycle 25 l/min	1.07	0.17	1.22	0.06	0.8	0.15	2.5	465	4.6	65	188.23	263.95	15.3	2.08	0.14	88.7
MIV-34	air rate and 15 l/min	1.06	0.17	1.21	0.01	0.5	0.15	1.5	465	5.0	65	207.99	291.21	8.5	1.22	0.14	53.8
MIV-35	air rate and 15 l/min	1.06	0.17	1.20	0.02	0.5	0.15	2.5	465	4.9	65	202.06	282.32	11.8	2.05	0.18	70.4
MIV-36	air rate and 15 l/min	1.06	0.17	1.21	0.01	0.5	0.15	2	465	5.0	65	207.05	289.72	9.2	1.63	0.17	56.2
MIV-37	air rate and 15 l/min	1.06	0.17	1.20	0.02	0.4	0.14	3	465	4.9	65	201.57	281.69	12.0	2.46	0.21	69.9
MIV-38	rtd and 30 l/min	1.53	0.17	1.71	0.04	0.9	0.19	1.5	465	3.3	65	198.33	275.82	14.8	1.24	0.09	80.5
MIV-39	air rate and 30 l/min	1.07	0.17	1.21	0.07	0.9	0.14	3	465	4.4	65	186.65	259.4	20.1	2.50	0.14	109.3
MIV-40	air rate and 30 l/min	1.03	0.17	1.17	0.07	0.9	0.13	2.5	465	4.6	65	187.11	260.01	19.9	2.08	0.11	109.2
MIV-41	air rate and 20 l/min	1.07	0.17	1.21	0.03	0.6	0.14	2.5	465	4.7	65	199.09	277.18	14.2	2.06	0.15	83.2
MIV-42	air rate and 20 l/min	1.05	0.17	1.20	0.03	0.6	0.15	3	465	4.7	65	196.87	274.14	15.1	2.47	0.17	86.8
MIV-43	air rate and 20 l/min	1.06	0.17	1.20	0.03	0.6	0.14	2	465	4.8	65	200.2	278.8	13.6	1.64	0.12	81.1
MIV-44	column height	1.04	0.17	1.20	0.05	0.9	0.16	1.5	310	2.8	65	39.05	112.51	18.8	1.42	0.08	101.9
MIV-45	column height	0.24	0.17	0.41	0.05	0.9	0.17	1.5	310	7.8	65	37.95	108.75	21.8	1.42	0.07	126.5
MIV-46	column height	2.10	0.17	2.33	0.03	0.9	0.23	1.5	310	1.5	65	39.53	114.88	16.7	1.41	0.10	82.2
MIV-47	column height	1.60	0.17	1.83	0.05	0.9	0.21	1.5	310	1.9	65	39.6	114.29	17.5	1.41	0.09	89.8
MIV-48	column height	0.56	0.17	0.68	0.06	0.9	0.12	1.5	310	4.8	65	38.42	110.29	20.6	1.42	0.07	116.6
MIV-50*	Long Term (6 hrs)	0.66	0.17	0.76	0.09	1.0	0.10	2.5	310	4.3	65	37.99	108.77	20.5	2.36	0.12	116.8

* Average values

C-2 Flotation efficiency and brightness gain results (Static Mixer Sparger)

Test	Brightness (ISO)			Column	Plant	ERIC (ppm)			Column	Plant
Series	Feed	Accepts	Plant	Gain	Gain	Feed	Accepts	Plant	Efficiency (%)	Efficiency (%)
MIV-1	46.1	54.95	57.5	8.85	11.4	934.14	344.9	216.5	63.1	76.8
MIV-2	45.16	53.16	55.6	8	10.44	949.2	329.6	236.3	65.3	75.1
MIV-3	46.66	53.26	56.68	6.6	10.02	879.56	343.7	243.14	60.9	72.4
MIV-4	47.22	56.56	58	9.34	10.78	845.8	263.7	184.5	68.8	78.2
MIV-5	46.43	52.62	57.07	6.19	10.64	764.9	414	206.9	45.9	73.0
MIV-6	47.54	58.57	59.02	11.03	11.48	858.96	203.9	189.38	76.3	78.0
MIV-7	46.93	58.94	58.04	12.01	11.11	908.1	173.9	206.1	80.9	77.3
MIV-8	46.4	54	57.71	7.6	11.31	963.4	421.3	229.1	56.3	76.2
MIV-9	47.59	58.04	58.4	10.45	10.81	806.7	197.2	193.42	75.6	76.0
MIV-10	45.26	56.39	57.31	11.13	12.05	1040.85	300.53	258.9	71.1	75.1
MIV-11	44.62	53.03	57.17	8.41	12.55	1122.1	482.1	268.2	57.0	76.1
MIV-12	46.11	59.19	56.99	13.08	10.88	987.9	151.3	283.1	84.7	71.3
MIV-13	44.58	55.99	56.3	11.41	11.72	1015.75	241.06	244.3	76.3	75.9
MIV-14	46.83	56.95	58.91	10.12	12.08	905.05	300.2	219.3	66.8	75.8
MIV-15	48.65	60.71	60.54	12.06	11.89	871.85	191.8	200.3	78.0	77.0
MIV-16	48.66	58.44	60.93	9.78	12.27	942.9	298.4	206.1	68.4	78.1
MIV-17	48.2	60.48	58.46	12.28	10.26	905.4	137.3	219.6	84.8	75.7
MIV-18	47.13	55.91	58.64	8.78	11.51	919.42	296.07	229.16	67.8	75.1
MIV-19	47.64	58.05	57.25	10.41	9.61	916.96	195.4	237.1	78.7	74.1
MIV-20	46.62	52.21	57.48	5.59	10.86	970.15	528.5	270.09	45.5	72.2
MIV-21	47.25	56.55	57.44	9.3	10.19	941.72	292.4	272.7	69.0	71.0
MIV-22	47.26	57.99	57.94	10.73	10.68	959.8	228.7	258.8	76.2	73.0
MIV-23	46.31	55.59	57.62	9.28	11.31	974.8	387.7	244.18	60.2	75.0
MIV-24	46.77	57.57	57.82	10.8	11.05	912.7	246.5	249.8	73.0	72.6
MIV-25	46.82	51.3	58.68	4.48	11.86	907.5	647.4	225.4	28.7	75.2
MIV-26	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
MIV-27	46.25	51.88	57	5.63	10.75	1052.5	556.9	288.8	47.1	72.6
MIV-28	48.57	56.48	58.76	7.91	10.19	944.9	326.3	243.9	65.5	74.2
MIV-29	49.6	60.9	60.65	11.3	11.05	800.6	183.5	200.8	77.1	74.9
MIV-30	47.86	60.03	59.43	12.17	11.57	921.57	221.08	195.3	76.0	78.8
MIV-31	46.2	51.32	58.04	5.12	11.84	1026.6	639.5	272.8	37.7	73.4
MIV-32	46.52	52.42	56.72	5.9	10.2	988.6	481.2	260.3	51.3	73.7
MIV-33	47.3	56.48	57.12	9.18	9.82	963.2	262.2	240.2	72.8	75.1
MIV-34	45.61	53.79	59.79	8.18	14.18	1092.7	459.02	189.9	58.0	82.6
MIV-35	46.02	54.58	59.76	8.56	13.74	1042.5	408.7	194.2	60.8	81.4
MIV-36	45.83	53.47	59.47	7.64	13.64	1070.9	411.1	210.4	61.6	80.4
MIV-37	44.79	54.43	57.74	9.64	12.95	1096.7	390.3	255.2	64.4	76.7
MIV-38	46.51	56.63	55.68	10.12	9.17	963.5	298.9	301.8	69.0	68.7
MIV-39	45.95	57.92	57.64	11.97	11.69	1035.5	241.2	271	76.7	73.8
MIV-40	45.38	58.16	58.37	12.78	12.99	997.6	197.2	207.4	80.2	79.2
MIV-41	46.62	57.07	59.4	10.45	12.78	946.6	244.6	169.8	74.2	82.1
MIV-42	46.22	55.86	59.69	9.64	13.47	938.6	262.4	173.9	72.0	81.5
MIV-43	47.11	57.77	59.57	10.66	12.46	916.8	248.6	175.7	72.9	80.8
MIV-44	46.11	57.76	57.57	11.65	11.46	1017.7	266.4	277.4	73.8	72.7
MIV-45	45.84	59.61	57.57	13.77	11.73	1045.1	164.3	275.1	84.3	73.7
MIV-46	44.07	53.09	56.95	9.02	12.88	1134.6	460.9	316.5	59.4	72.1
MIV-47	45.2	55.17	57.17	9.97	11.97	1078.7	366.4	296.4	66.0	72.5
MIV-48	45.56	58.51	57.44	12.95	11.88	1024.3	209.9	277.7	79.5	72.9
MIV-50*	47.56	59.45	60.38	11.89	12.82	929.7	206.9	183.3	77.7	80.3

* Average values

C-3 Flow rate, consistency, organic content, and standard deviation data (Static Mixer Sparger)

Test	Mean Flow Rates (l/min)				Flow Rates-Std Dev. (l/min)				Mean Consistency (%)			Consistency Std Dev. (%)*			Organics (%)			Organics Std Dev. (%)*		
Series	Feed	Wash Water	Accepts	Rejects	Feed	Wash Water*	Accepts	Rejects*	Feed	Accepts	Rejects	Feed	Accepts	Rejects	Feed	Accepts	Rejects	Feed	Accepts	Rejects
MIV-1	5.04	0.83	5.83	0.033	0.04	0.1	0.25	0.1	1.26	1.1	1.37	0.02	0.01	0.25	87.06	89.17	56.59	0.36	0.32	2.21
MIV-2	5.06	0.83	5.81	0.111	0.05	0.1	0.34	0.1	1.23	1.11	0.51	0.02	0.01	0.25	87.91	90.06	58.99	0.36	0.32	2.21
MIV-3	5.05	0.83	5.83	0.093	0.06	0.1	0.37	0.1	1.3	1.18	0.45	0.02	0.01	0.25	87.62	89.91	56.56	0.36	0.32	2.21
MIV-4	5.01	0.83	5.76	0.089	0.05	0.1	0.35	0.1	1.23	1.05	0.62	0.02	0.01	0.25	88.84	91.12	55.57	0.36	0.32	2.21
MIV-5	5.02	0.83	5.81	0.052	0.07	0.1	0.22	0.1	1.32	1.09	0.23	0.02	0.01	0.25	88.52	90.3	55.9	0.36	0.32	2.21
MIV-6	5.09	0.83	5.86	0.07	0.15	0.1	0.36	0.1	1.22	1.03	0.63	0.02	0.01	0.25	87.26	90.21	56.74	0.36	0.32	2.21
MIV-7	5.02	0.83	5.62	0.307	0.06	0.1	0.47	0.1	1.26	1.09	1.11	0.02	0.01	0.25	87.21	90.86	52.12	0.36	0.32	2.21
MIV-8	5.03	0.83	5.93	0.038	0.06	0.1	0.34	0.1	1.33	1.1	0.66	0.02	0.01	0.25	87.78	89.55	55.8	0.36	0.32	2.21
MIV-9	5.04	0.83	5.82	0.195	0.05	0.1	0.37	0.1	1.29	1.11	1.35	0.02	0.01	0.25	88.22	90.58	55.3	0.36	0.32	2.21
MIV-10	5.14	0.81	5.92	0.144	0.16	0.1	0.34	0.1	1.15	0.98	1.01	0.02	0.01	0.25	86	90.8	39.91	0.36	0.32	2.21
MIV-11	10.74	0.81	11.59	0.144	0.10	0.1	0.30	0.1	1.33	1.19	2.41	0.02	0.01	0.25	86.81	89.47	42.13	0.36	0.32	2.21
MIV-12	1.19	0.81	1.91	0.154	0.14	0.1	0.61	0.1	1.28	0.75	0.56	0.02	0.01	0.25	86	92.02	39.2	0.36	0.32	2.21
MIV-13	3.13	0.81	3.91	0.105	0.07	0.1	0.28	0.1	1.28	0.98	0.7	0.02	0.01	0.25	87.04	91.74	42.93	0.36	0.32	2.21
MIV-14	7.85	0.81	8.69	0.097	0.19	0.1	0.31	0.1	1.64	1.23	0.65	0.02	0.01	0.25	86.96	88.8	53.86	0.36	0.32	2.21
MIV-15	5.1	0.81	5.94	0.161	0.05	0.1	0.36	0.1	1.23	1.05	1.47	0.02	0.01	0.25	86.99	90.21	47.56	0.36	0.32	2.21
MIV-16	10.6	0.81	11.62	0.183	0.08	0.1	0.32	0.1	1.26	1.17	2.39	0.02	0.01	0.25	88.46	90.01	51.73	0.36	0.32	2.21
MIV-17	1.13	0.81	1.89	0.219	0.15	0.1	0.96	0.1	1.29	1.07	0.35	0.02	0.01	0.25	87.46	93.53	43.29	0.36	0.32	2.21
MIV-18	7.71	0.81	8.88	0.084	0.07	0.1	0.50	0.1	1.25	1.16	3.07	0.02	0.01	0.25	87.95	90.66	46.92	0.36	0.32	2.21
MIV-19	2.74	0.81	3.55	0.206	0.09	0.1	0.92	0.1	1.29	1.02	1.14	0.02	0.01	0.25	86.99	92.72	39.8	0.36	0.32	2.21
MIV-20	5.14	0.81	5.86	0.0296	0.14	0.1	0.30	0.1	1.13	0.98	2.86	0.02	0.01	0.25	88.01	90.34	60.34	0.36	0.32	2.21
MIV-21	5.14	0.81	5.94	0.101	0.05	0.1	0.38	0.1	1.16	1.04	1.69	0.02	0.01	0.25	88.79	92.22	53.34	0.36	0.32	2.21
MIV-22	5.05	0.81	5.76	0.199	0.06	0.1	0.44	0.1	1.23	1.11	1.25	0.02	0.01	0.25	88.81	91.01	51.96	0.36	0.32	2.21
MIV-23	5.01	0.82	5.74	0.085	0.06	0.1	0.46	0.1	1.18	1.04	3.09	0.02	0.01	0.25	88.37	91.1	55.2	0.36	0.32	2.21
MIV-24	5.02	0.81	5.75	0.192	0.06	0.1	0.38	0.1	1.21	1.02	0.88	0.02	0.01	0.25	88.95	91.84	53.31	0.36	0.32	2.21
MIV-25	4.99	0.8	5.69	0.01	0.06	0.1	0.43	0.1	1.19	1.03	0.99	0.02	0.01	0.25	88.62	90.65	53.42	0.36	0.32	2.21
MIV-26	4.99	0.81	5.67	na	n/a	n/a	n/a	n/a	n/a	n/a	n/a	0.02	0.01	0.25	89.12	90.54	55.67	0.36	0.32	2.21
MIV-27	5.05	0.81	5.74	0.051	0.05	0.1	0.19	0.1	1.14	0.96	1.69	0.02	0.01	0.25	89.14	90.2	57.32	0.36	0.32	2.21
MIV-28	5.1	0.82	5.87	0.092	0.05	0.1	0.26	0.1	1.17	0.99	1.66	0.02	0.01	0.25	87.93	90.51	61.45	0.36	0.32	2.21
MIV-29	5.12	0.81	5.84	0.256	0.06	0.1	0.41	0.1	1.22	1.04	1.44	0.02	0.01	0.25	86.45	88.58	59.55	0.36	0.32	2.21
MIV-30	5.13	0.81	5.78	0.338	0.05	0.1	0.46	0.1	1.15	0.99	1.2	0.02	0.01	0.25	87.65	90.09	58.09	0.36	0.32	2.21
MIV-31	5.14	0.81	5.79	0.028	0.05	0.1	0.33	0.1	1.16	1	2.7	0.02	0.01	0.25	88.03	89.81	64.25	0.36	0.32	2.21
MIV-32	5.13	0.8	5.79	0.117	0.05	0.1	0.29	0.1	1.16	1.01	1.6	0.02	0.01	0.25	88.74	89.95	64.8	0.36	0.32	2.21
MIV-33	5.13	0.81	5.84	0.27	0.05	0.1	0.29	0.1	1.15	0.99	1.4	0.02	0.01	0.25	88.62	89.84	62.1	0.36	0.32	2.21
MIV-34	5.11	0.81	5.82	0.038	0.04	0.1	0.25	0.1	1.02	0.92	2.26	0.02	0.01	0.25	88.5	90.48	60.91	0.36	.32	2.21
MIV-35	5.08	0.83	5.78	0.074	0.05	0.1	0.37	0.1	1.14	0.97	3.17	0.02	0.01	0.25	87.77	89.48	60.99	0.36	0.32	2.21
MIV-36	5.11	0.81	5.83	0.045	0.06	0.1	0.30	0.1	1.15	1.05	3.12	0.02	0.01	0.25	88.17	90.33	60.12	0.36	0.32	2.21
MIV-37	5.08	0.81	5.75	0.098	0.06	0.1	0.33	0.1	1.14	0.98	1.49	0.02	0.01	0.25	87.83	89.62	60.29	0.36	0.32	2.21
MIV-38	7.35	0.82	8.24	0.201	0.07	0.1	0.37	0.1	1.21	1.06	2.27	0.02	0.01	0.25	87.88	90.51	49.29	0.36	0.32	2.21
MIV-39	5.16	0.81	5.83	0.314	0.15	0.1	1.06	0.1	1.17	0.98	1.63	0.02	0.01	0.25	87.73	90.86	54.35	0.36	0.32	2.21
MIV-40	4.97	0.81	5.61	0.335	0.09	0.1	1.23	0.1	1.16	1.03	0.97	0.02	0.01	0.25	88.32	91.44	53.83	0.36	0.32	2.21
MIV-41	5.13	0.83	5.82	0.159	0.07	0.1	0.31	0.1	1.11	1	1.62	0.02	0.01	0.25	87.68	90.67	56.46	0.36	0.32	2.21
MIV-42	5.07	0.81	5.77	0.143	0.05	0.1	0.34	0.1	1.14	0.99	0.87	0.02	0.01	0.25	88.79	90.25	55.31	0.36	0.32	2.21
MIV-43	5.11	0.81	5.78	0.122	0.15	0.1	0.42	0.1	1.08	0.96	0.57	0.02	0.01	0.25	88.72	90.89	56.4	0.36	0.32	2.21
MIV-44	5	0.81	5.79	0.224	0.06	0.1	0.37	0.1	1.2	1	1.69	0.02	0.01	0.25	86.76	89.4	48.68	0.36	0.32	2.21
MIV-45	1.15	0.81	1.97	0.218	0.13	0.1	1.06	0.1	1.16	0.79	0.51	0.02	0.01	0.25	87.37	92.07	47.33	0.36	0.32	2.21
MIV-46	10.11	0.81	11.2	0.14	0.72	0.1	0.83	0.1	1.2	1.1	2.94	0.02	0.01	0.25	87.8	89.74	55.24	0.36	0.32	2.21
MIV-47	7.7	0.82	8.69	0.217	0.22	0.1	0.44	0.1	1.22	1.15	1.51	0.02	0.01	0.25	87.97	90.94	53.06	0.36	0.32	2.21
MIV-48	2.67	0.81	3.27	0.271	0.10	0.1	0.91	0.1	1.16	1.02	0.89	0.02	0.01	0.25	88.1	91.58	52.52	0.36	0.32	2.21
MIV-50**	3.16	0.81	3.64	0.442	0.17	0.1	0.87	0.1	1.16	0.99	0.78	0.02	0.01	0.25	87.85	92.25	59.6	0.36	0.32	2.21

* Calculated from experimental error test   ** Average values

C-4 Material balanced data (Static Mixer Sparger)

Test	Feed				Accepts				Rejects				Wash Water	Reject	Ash	Ink Recovery	Organic
Series	ml/min	% Solids	% Organic	% Ash	ml/min	% Solids	% Organic	% Ash	ml/min	% Solids	% Organic	% Ash	ml/min	Rate (%)	Loss (%)	(%)	Loss (%)
MIV-1	5326.7	1.2	88.05	11.95	5820.4	1.03	88.39	11.61	39.6	1.62	56.19	43.81	833.2	0.8	3.9	63.3	0.7
MIV-2	5068.8	1.27	88.87	11.13	5782.8	1.1	89.32	10.69	113.9	0.82	58.47	41.53	827.9	2.2	5.4	65.7	1.0
MIV-3	5068.6	1.35	88.70	11.30	5799.8	1.17	89.06	10.94	96.3	0.78	56.11	43.89	827.5	1.9	4.3	61.2	0.7
MIV-4	5004.3	1.22	89.81	10.19	5743.9	1.05	89.81	10.19	90.6	1.66	55.00	45.00	830.1	1.8	10.9	69.2	1.5
MIV-5	5012.5	1.28	89.44	10.56	5795.1	1.1	89.57	10.43	49.9	0.5	55.86	44.15	832.6	1.0	1.6	46.2	0.2
MIV-6	5047.1	1.2	88.66	11.34	5805.2	1.03	89.12	10.88	72	1.15	56.02	43.98	830.2	1.4	5.3	76.6	0.9
MIV-7	4984.2	1.29	87.58	12.42	5500.5	1.08	87.58	12.42	311	1.57	51.05	48.95	827.3	6.2	29.9	82.3	4.4
MIV-8	5014.2	1.29	88.68	11.32	5807.5	1.11	88.84	11.16	38.8	0.83	55.63	44.37	832.1	0.8	2.0	56.4	0.3
MIV-9	5054.1	1.31	88.57	11.43	5685.8	1.11	90.31	9.69	197.7	1.63	54.65	45.35	829.4	3.9	19.3	76.7	3.0
MIV-10	4991.4	1.16	87.07	12.93	5651.9	0.97	90.00	10.00	148	2.2	37.65	62.35	808.6	3.0	27.1	72.7	2.4
MIV-11	10720.7	1.31	87.51	12.49	11390.6	1.19	88.93	11.07	150.6	2.78	41.34	58.66	820.6	1.4	14.0	58.5	1.4
MIV-12	1344	1.3	86.24	13.77	1993.1	0.78	91.85	8.15	157.8	1.16	38.27	61.73	807	11.7	47.0	86.4	4.6
MIV-13	2899.5	1.28	88.01	12.00	3599.6	0.97	91.02	8.98	108.3	2.07	40.75	59.25	808.3	3.7	29.8	77.7	2.8
MIV-14	7632.8	1.45	87.78	12.22	8364.8	1.31	88.16	11.84	88.4	1.37	53.52	46.48	820.5	1.2	4.2	67.2	0.7
MIV-15	5097.3	1.24	87.63	12.37	5741.7	1.05	89.73	10.27	165	1.85	46.39	53.61	809.4	3.2	20.9	79.0	2.6
MIV-16	10617.3	1.28	88.60	11.41	11241.7	1.16	89.91	10.09	185.3	2.5	51.56	48.44	809.8	1.7	14.5	69.6	2.0
MIV-17	2036.7	1.45	88.30	11.70	2596.1	1.03	92.93	7.07	234.9	1.11	40.50	59.50	794.3	11.5	44.9	86.3	4.0
MIV-18	7731.8	1.3	88.69	11.31	8444.3	1.15	90.09	9.91	136.2	3.32	46.03	53.97	808.7	1.8	21.5	68.9	2.3
MIV-19	2788.3	1.34	87.42	12.58	3380.4	1	92.41	7.59	212.9	1.62	38.30	61.70	805.1	7.6	45.3	80.7	4.0
MIV-20	5113.1	1.15	88.88	11.12	5872.6	0.97	89.67	10.33	49.3	3.09	59.49	40.52	808.9	1.0	9.4	47.2	1.7
MIV-21	5126.8	1.21	89.81	10.19	5821.8	1.02	91.44	8.56	111.9	2.28	51.76	48.25	806.9	2.2	19.5	70.3	2.4
MIV-22	5070.3	1.28	89.13	10.87	5676.8	1.1	90.77	9.23	201.2	1.35	51.46	48.54	807.6	4.0	18.7	77.1	2.4
MIV-23	5000.1	1.23	88.90	11.10	5712.6	1.02	90.71	9.30	94.5	3.23	54.22	45.78	807	1.9	20.5	62.3	3.0
MIV-24	5016.4	1.21	89.50	10.50	5633.2	1.02	91.41	8.57	195.4	1.54	52.29	47.71	810.2	3.9	22.3	74.4	2.9
MIV-25	5060.5	1.19	88.56	11.44	5675.2	1.03	90.84	9.16	40.2	0.95	53.26	46.74	807.5	0.8	2.6	30.8	0.4
MIV-26	5055.3	n/a	n/a	n/a	5665.2	n/a	n/a	n/a	n/a	n/a	n/a	n/a	810.2	n/a	n/a	n/a	n/a
MIV-27	5055.1	1.13	89.39	10.61	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	57.14	42.86	810.8	1.1	7.6	47.8	1.2
MIV-28	5098.4	1.17	88.79	11.21	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	810	2.0	12.8	66.7	2.5
MIV-29	5120.5	1.23	86.64	13.36	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	809.7	4.0	18.7	78.5	4.2
MIV-30	5123.8	1.16	87.68	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	809.1	6.6	25.3	77.9	4.9
MIV-31	5136.1	1.17	88.74	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	809.1	0.8	6.6	36.8	1.5
MIV-32	5130.4	1.12	89.14	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	810.4	2.8	11.8	52.1	2.1
MIV-33	5130	1.15	88.96	11.04	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	809.6	5.3	17.3	73.3	3.3
MIV-34	5112.6	1.07	89.22	10.78	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	808	1.0	4.5	59.0	0.8
MIV-35	5087	1.15	88.07	11.93	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	809.5	1.5	13.7	62.2	2.8
MIV-36	5101.9	1.22	88.51	11.49	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	806.5	1.2	8.3	62.8	1.5
MIV-37	5071.9	1.15	88.35	11.65	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	809.4	2.0	10.2	65.4	2.0
MIV-38	7351	1.22	87.98	12.02	7955.4	1.06	87.98	12.02	209.4	2.58	49.06	50.94	809.8	2.8	25.0	70.8	3.3
MIV-39	5149.3	1.17	87.75	12.25	5644.9	0.98	90.85	9.15	314.2	1.63	54.29	45.71	809.8	6.1	31.7	78.6	5.3
MIV-40	4968.3	1.19	88.68	11.32	5438.9	1.02	88.68	11.32	337.5	1.14	52.94	47.06	808.1	6.8	27.1	81.5	3.9
MIV-41	5117.1	1.17	88.31	11.70	5758.2	0.98	90.20	9.80	165.7	1.96	55.18	44.82	806.9	3.2	20.8	75.6	3.4
MIV-42	5082.6	1.15	89.10	10.90	5748.3	1.15	90.01	9.99	144.2	1.05	55.01	45.00	810	2.8	10.7	68.4	1.6
MIV-43	5125.9	1.1	89.52	10.48	5810.6	0.95	90.27	9.73	124.2	1.49	55.75	44.26	808.8	2.4	13.9	71.5	2.0
MIV-44	5016.5	1.2	86.80	13.20	5603.8	1.2	89.37	10.63	223.4	1.69	48.59	51.41	810.7	4.5	24.4	70.8	3.5
MIV-45	1458.3	1.2	87.55	12.45	2038.4	0.78	91.94	8.06	224.2	0.76	46.67	53.33	804.2	15.4	41.7	85.7	5.2
MIV-46	10186.6	1.21	88.19	11.81	10851.5	1.1	89.45	10.55	144.8	3.09	54.71	45.29	809.7	1.4	13.9	60.7	2.3
MIV-47	7721.9	1.27	88.76	11.24	8308.7	1.14	90.34	9.66	221.3	1.83	51.84	48.16	808.1	2.9	17.7	67.2	2.4
MIV-48	2751.5	1.25	88.74	11.26	3279	1	90.61	9.39	275.3	0.61	52.25	47.75	802.7	10.0	20.7	80.5	2.9
MIV-50*	3256.3	1.22	88.26	11.74	3615.7	0.98	91.33	8.67	446.4	0.96	57.93	42.07	805.9	13.7	38.7	80.2	7.1

* Average values

D-1 Mass balanced data (Long Term Tests)

MIV-50 Static Mixer Sparger

Sample Number	Time (hours)	Feed				Accepts				Rejects			Wash Water ml/min	Ink Recovery (%)	Organic Loss (%)
		Ink (ppm)	ml/min	Consis. (%)	Organic (%)	Ink (ppm)	ml/min	Consis. (%)	Organic (%)	ml/min	Consis. (%)	Organic (%)			
MIV-50a	0.5	945.7	3344.5	1.26	87.32	233.6	3691.6	1.01	87.32	455.2	1.05	52.94	802.2	78.1	6.88
MIV-50b	1.25	932.2	3297	1.21	87.97	213.3	3630.1	0.98	91.49	472.1	0.89	58.10	805.2	79.6	6.96
MIV-50c	2.25	892	3187.7	1.17	88.38	214.25	3564.9	0.94	91.92	430.1	0.91	57.93	807.3	78.4	6.88
MIV-50d	3.25	959.9	3312.2	1.22	87.92	222.4	3734.4	0.98	90.97	382.6	0.94	56.91	804.8	79.0	5.76
MIV-50e	4.25	907.1	3284.1	1.24	88.76	230.8	3642.2	0.99	93.05	446.1	1.05	55.80	804.2	77.5	7.23
MIV-50f	5.25	898.6	3261.6	1.19	88.30	229.9	3590.9	0.95	92.29	477	1.02	60.31	806.3	77.5	8.56
MIV-50g	6.25	972.6	3106.9	1.23	89.16	244.2	3456	0.98	92.27	461.9	0.89	63.51	811.1	77.7	7.66
	Average	929.7	3256.3	1.22	88.26	226.9	3615.7	0.98	91.33	446.4	0.96	57.928	805.9	78.3	7.13
	Std Dev.	31.4	82.0	0.03	0.60	11.1	90.8	0.02	1.88	32.3	0.07	3.349	2.8	0.8	0.85
	Rel. Std Dev.	3.4	2.5	2.50	0.68	4.9	2.5	2.43	2.06	7.2	7.62	5.782	0.3	1.0	12.0
	Std Error	4.5	11.7	0.00	0.09	1.6	13.0	0.00	0.27	4.6	0.01	0.478	0.4	0.1	0.12
	+/- (90 %)	8.7	22.8	0.01	0.17	3.1	25.2	0.01	0.52	9.0	0.02	0.930	0.8	0.2	0.2

ISP- 52 Porous Sparger

Sample Number	Time (hours)	Feed				Accepts				Rejects			Wash Water ml/min	Ink Recovery (%)	Fiber Loss (%)
		Ink (ppm)	ml/min	Consis. (%)	Organic (%)	Ink (ppm)	ml/min	Consis. (%)	Organic (%)	ml/min	Consis. (%)	Organic (%)			
ISP-52a	0.5	950.6	3010.7	1.24	89.328	233.2	3228.2	1.08	91.76	588.2	0.42	55.36	805.7	77.1	4.10
ISP-52b	1.17	965	3157.5	1.23	89.425	224	3434.8	1.05	92.05	528.4	0.53	55.48	805.6	78.4	4.47
ISP-52c	2.17	963.5	3115.5	1.22	88.91	247.3	3472.4	1	91.72	451.1	0.7	58.07	807.1	76.6	5.43
ISP-52d	3.17	910.4	3110.2	1.25	88.42	251.8	3612	0.99	91.51	305.5	1.02	52.87	807.4	74.6	4.79
ISP-52e	4.17	826.8	2902.4	1.24	87.087	253.9	3486.7	0.96	89.71	225.3	0.96	53.57	809.6	71.4	3.70
ISP-52f	5.17	841.9	3082.4	1.21	87.674	266.5	3693	0.97	89.06	196.2	0.75	54.06	806.8	69.6	2.43
ISP-52g	6.17	905.1	2892.6	1.34	87.32	270.8	3481.9	1.04	89.39	218.8	1.03	53.97	808.2	72.0	3.59
	Average	**909.0**	**3038.8**	**1.25**	**88.31**	**249.6**	**3487.0**	**1.01**	**90.74**	**359.1**	**0.77**	**54.77**	**807.2**	**74.2**	**4.1**
	Std Dev.	56.4	106.3	0.04	0.96	16.8	146.1	0.04	1.29	161.6	0.24	1.73	1.4	3.3	1.0
	Rel. Std Dev.	6.2	3.5	3.46	1.09	6.7	4.2	4.40	1.42	45.0	31.32	3.16	0.2	4.4	23.7
	Std Error	21.3	40.2	0.02	0.36	6.3	55.2	0.02	0.49	61.1	0.09	0.65	0.5	1.2	0.4
	+/- (90 %)	41.4	78.0	0.03	0.71	12.3	107.3	0.03	0.95	118.6	0.18	1.27	1.0	2.4	0.7
	Average*	**857.9**	**2959.1**	**1.26**	**87.36**	**263.7**	**3553.9**	**0.99**	**89.39**	**213.4**	**0.91**	**53.86**	**808.2**	**71.0**	**3.2**
	Std Dev.*	41.5	106.9	0.07	0.30	8.8	120.5	0.04	0.33	15.3	0.15	0.26	1.4	1.3	0.7
	Rel. Std Dev.	4.8	3.6	5.39	0.34	3.3	3.4	4.40	0.37	7.2	15.95	0.48	0.2	1.8	21.7
	Std Error	24.0	61.7	0.04	0.17	5.1	69.6	0.03	0.19	8.8	0.08	0.15	0.8	0.7	0.4
	+/- (90 %)	70.0	180.2	0.11	0.50	14.8	203.2	0.07	0.55	25.8	0.25	0.44	2.4	2.2	1.2

* Average of last three samples

D-2 Scale-up parameters based on long term tests

Parameters	ISP-52*		M1V-50	
Column Height (cm):	310		310	
Column Diameter (cm):	10.1		10.1	
Froth Depth (cm):	65		65	
Sparger Type:	0.5 micron SS sparger		1 inch static mixer	
Sparger Liquid Flow Rate:	NA		32	
	cm	S.G.	cm	S.G.
Estimated Ink Particle Size/Density:	0.004	1.4	0.004	1.4
Estimated Fiber Particle Size/Density	0.2	1	0.2	1
Estimated Ash Particle Size/Density:	0.004	2.2	0.004	2.2
	L/min	cm/s	L/min	cm/s
Corrected Air Rate:	12	2.5	11.3	2.4
Feed Rate:	2.92	0.61	3.16	0.66
Wash Water Rate:	0.81	0.17	0.81	0.17
Accepts Rate:	3.39	0.71	3.64	0.76
Rejects Rate:	0.21	0.04	0.44	0.09
Bias Rate:	0.48	0.1	0.48	0.1
Liquid Density (g/cm3):	1		1	
Feed Slurry Density (g/cm3):	1.003		1.002	
Feed (% Solids):	1.24		1.16	
Accepts (% Solids):	1		0.99	
Rejects (% Solids):	0.94		0.78	
Residence Time (min):	5		4.3	
Gas Holdup (%):	14.9		20.5	
Bubble Size (cm):	0.16		0.12	
Superficial Bubble Area Rate (1/s):	95		117	
Brightness Gain (ISO):	9.76		10.03	
Flotation Efficiency (%):	69.2		77.8	
Ink Recovery (%):	71.3		77.7	
Ink Recovery (% of max 84%):	**84.9**		**92.5**	
Fiber Recovery to Rejects (%):	**3.24**		**7.13**	
Ash Recovery to Rejects (%):	**19.14**		**38.9**	

*** Average of last three samples**

E-1 Material balanced data for surveys 1 and 2

Survey #1 Unbalanced data

Sample	Feed				Accepts				Rejects			Wash Water	Flotation
Number	(l/min)	Ink (ppm)	% Solids	Organic %	(l/min)	Ink (ppm)	% Solids	Organic %	(l/min)	% Solids	Organic %	(l/min)	Efficiency (%)
1	14500	996.6	1.22	87.76	17200	255.3	1.1	90.83	528	2.18	51.73	1488	74.4
2	14100	1021.1	1.24	89.11	16222	252.4	1.12	90.95	375	3.29	54.34	1510	75.3
3	15500	1094	1.32	88.53	17750	257.9	1.16	91.23	393	2.19	53.86	1531	76.4
4	15527	1069.9	1.25	88.15	18000	262.3	1.06	90.67	649	2.58	53.97	1553	75.5
Average	14906.8	1045.4	1.26	88.39	17293.0	257.0	1.11	90.92	486.3	2.56	53.5	1520.5	75.4
Std Dev.	719.5	44.5	0.04	0.54	788.3	4.2	0.04	0.22	128.2	0.52	1.20	600.0	0.8

Survey #1 material balanced data

Sample	Feed				Accepts				Rejects			Wash Water	Reject	Ink	Fiber
Number	(l/min)	Ink (ppm)	% Solids	Organic %	(l/min)	Ink (ppm)	% Solids	% Fiber	(l/min)	% Solids	Organic %	(l/min)	Rate (%)	Recovery (%)	Loss (%)
1	15214	996.6	1.24	88.00	17200	255.3	1.08	90.81	564.1	2.4	51.69	1632.6	3.7	74.8	4.2
2	14597.1	1021.1	1.28	89.02	15381.6	252.4	1.15	90.96	312.4	3.17	54.35	1096.9	2.1	76.6	3.2
3	15894.6	1094	1.32	88.82	17137.2	257.9	1.15	91.21	484.2	2.78	53.82	1726.9	3.0	77.9	3.9
4	15889.2	1045.4	1.24	88.00	17262.9	262.3	1.06	90.68	590.3	2.44	54.00	1964	3.7	76.7	4.5
Average	15398.7	1039.3	1.27	88.46	16745.4	257.0	1.11	90.91	487.8	2.70	53.46	1605.1	3.2	76.5	4.0
Std Dev.	622.7	41.6	0.04	0.54	910.7	4.2	0.05	0.22	125.3	0.36	1.20	366.4	0.7	1.3	0.5
Rel. Std Dev.	4.0	4.0	3.02	0.61	5.4	1.6	4.23	0.25	25.7	13.28	2.25	22.8	21.6	1.7	13.6
Rel. Error	311.3	20.8	0.02	0.27	455.3	2.1	0.02	0.11	62.7	0.18	0.60	183.2	0.4	0.6	0.3
+/- (90 %)	732.58	48.91	0.05	0.63	1071.40	4.94	0.06	0.26	147.42	0.42	1.41	431.03	0.88	1.50	0.63

Survey #2 Unbalanced data for long term test comparison

Sample	Feed				Accepts				Rejects			Wash Water	Flotation
Number	(l/min)	Ink (ppm)	% Solids	Organic %	(l/min)	Ink (ppm)	% Solids	Organic %	(l/min)	% Solids	Organic %	(l/min)	Efficiency (%)
1	15500	1075	1.32	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	52.84	1508	75.4
2	14300	1024.6	1.28	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	55.42	1511	74.9
3	15640	1075.6	1.33	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	52.75	1490	74.6
4	15645	998.6	1.25	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	54.24	1560	72.4
Average	15271.3	1043.5	1.30	[illegible]	[illegible]	[illegible]	1.14	91.1	[illegible]	2.55	53.81	1542.8	74.3
Std Dev.	651.0	18.3	0.04	0.54	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.44	1.20	600.0	1.1

Survey #2 Balanced data for long term test comparison

Sample	Feed				Accepts				Rejects			Wash Water	Reject	Ink	Fiber
Number	(l/min)	Ink (ppm)	% Solids	Organic %	(l/min)	Ink (ppm)	% Solids	Organic %	(l/min)	% Solids	Organic %	(l/min)	Rate (%)	Recovery (%)	Loss (%)
1	16177.4	1075	1.34	88.80	17725	264.2	1.17	91.25	586.1	2.36	52.78	1738	3.6	76.5	1.8
2	14886.9	1024.6	1.28	89.28	16011.7	257.6	1.11	90.62	242.9	3.00	55.53	1967	1.6	75.7	2.4
3	16009	1075.6	1.33	89.06	17860	273.2	1.15	91.73	485.5	2.98	52.59	1892.4	3.0	75.7	4.0
4	17564.8	998.6	1.26	88.94	17564.8	275.6	1.10	90.80	471.6	2.20	54.33	1847	2.7	75.9	2.9
Average	16159.5	1043.5	1.30	88.46	17440.4	267.7	1.13	90.91	446.5	2.64	53.46	1861.1	2.7	75.9	3.3
Std Dev.	1098.1	38.3	0.04	0.54	565.5	8.3	0.03	0.22	145.0	0.42	1.20	95.8	0.8	0.4	0.8
Rel. Std Dev.	6.8	3.7	2.97	0.61	3.2	3.1	2.80	0.25	32.5	15.76	2.25	5.1	30.5	0.5	23.6
Rel. Error	549.0	19.1	0.02	0.27	282.7	4.2	0.02	0.11	72.5	0.21	0.60	47.9	0.4	0.2	0.4
+/- (90 %)	1291.89	45.04	0.05	0.63	665.28	9.77	0.04	0.26	170.62	0.49	1.41	112.74	0.98	0.44	0.91

F-1 Bubble size and superficial bubble area rate calculations (Watson, 1996)

Test Series	Sparger Type	J_g (cm/s)	J_l (cm/s)	E_g (%)	U_{bs} (cm/s)	Re_g	U_t (cm/s)	d_b (cm)	S_b (s^{-1})
openA-1	0.5 um	2	0.64	34.6	6.76	56.33	15.80	0.077	155.3
openA-2	0.5 um	4	0.65	24.6	17.14	392.53	30.13	0.184	130.5
openA-3	0.5 um	1	0.83	15.9	7.28	65.36	10.29	0.065	92.8
openA-4	0.5 um	3	0.65	24.3	13.20	223.89	23.04	0.136	132.7
openA-5	0.5 um	1.5	0.83	22.9	7.62	71.60	12.83	0.074	121.8
openA-6	0.5 um	1.5	1.46	34.8	6.55	52.94	15.41	0.075	119.7
openA-7	0.5 um	1.5	0.87	31.5	6.04	45.16	12.85	0.066	136.1
openA-8	0.5 um	1.5	0.49	29.3	5.81	41.87	11.63	0.062	145.6
openA-9	0.5 um	1.5	1.10	32.3	6.27	48.64	13.67	0.069	129.7
openA-10	0.5 um	1.5	0.67	30.3	5.91	43.32	12.17	0.064	141.2
openA-11	0.5 um	1.5	0.80	34.5	5.57	38.61	12.98	0.064	140.3
openA-12	0.5 um	1.5	0.89	22.6	7.79	74.87	13.00	0.075	119.7
openA-13	0.5 um	1.5	0.95	20.9	8.38	86.83	13.39	0.079	113.5
openA-14	0.5 um	1.5	0.84	20.8	8.27	84.48	13.19	0.078	115.2
openA-15	0.5 um	1.5	0.83	21.8	7.95	78.10	12.99	0.076	118.4
openA-16	0.5 um	1.5	0.82	18.1	9.29	107.15	13.85	0.085	105.5
openA-17	0.5 um	1.5	0.83	16.9	9.89	121.97	14.31	0.090	100.2
openA-18	0.5 um	1.5	0.79	21.0	8.16	82.16	13.06	0.077	116.6
openA-19	0.5 um	1.5	0.75	20.9	8.12	81.40	12.98	0.077	117.2
openA-20	0.5 um	1.5	0.75	20.4	8.29	84.88	13.09	0.078	115.5
openA-21	0.5 um	1.5	0.75	20.6	8.23	83.60	13.05	0.078	116.1
openB-1	100 um	2	0.90	7.3	28.44	1197.37	33.09	0.275	43.6
openB-2	100 um	1	0.90	4.1	25.57	944.96	27.78	0.233	25.7
openB-3	100 um	4.0	0.93	13.0	32.14	1572.59	42.43	0.341	71.0
openB-4	100 um	5.0	0.95	15.2	34.01	1785.08	47.27	0.375	79.9
openB-5	100 um	3.1	0.93	11.7	27.53	1113.11	35.31	0.278	67.0
openB-7	100 um	2	0.99	8.3	25.15	910.72	29.91	0.239	50.2
openB-8	100 um	2	0.59	9.0	22.82	734.80	27.57	0.214	56.0
openB-9	100 um	2	1.55	8.0	26.62	1033.56	31.47	0.256	46.9
openB-10	100 um	2	0.89	7.8	26.64	1034.97	31.33	0.255	47.0
openB-11	100 um	2	0.45	8.6	23.69	798.32	28.38	0.223	53.7
openB-12	100 um	2	1.13	7.8	26.87	1054.71	31.60	0.258	46.5
openB-13	100 um	2	0.67	7.9	26.17	995.14	30.83	0.250	48.0
openB-14	100 um	3	0.68	10.3	29.97	1345.22	37.22	0.303	59.4
openB-15	100 um	3	0.67	10.8	28.45	1198.15	35.78	0.286	62.9
openB-16	100 um	3	0.67	11.0	27.98	1153.99	35.33	0.281	64.1
openB-17	100 um	3	0.68	11.3	27.25	1087.98	34.65	0.273	66.0
openB-18	100 um	3	0.64	11.7	26.34	1009.63	33.80	0.263	68.5
openB-19	100 um	3	0.63	11.0	28.10	1165.82	35.44	0.282	63.8
openB-20	100 um	3	0.60	10.7	28.74	1224.88	36.03	0.289	62.3
openB-21	100 um	3	0.60	11.0	27.87	1144.53	35.21	0.280	64.4

F-2 Flotation column test data (Watson, 1996)

Test	Corrected flow rates (ml/min)			Consistency (%)			Ash Content (%)			Organic Content (%)			Eric (ppm)		Flotation	Ink	Organic
Series	Feed	Accepts	Rejects	Feed	Accepts	Rejects	Feed	Accepts	Rejects	Feed	Accepts	Rejects	Feed	Accepts	Efficiency (%)	Recovery (%)	Loss (%)
openA-1	47.1	51.4	13.6	1.14	0.98	0.33	11.37	7.45	54.09	88.63	92.55	45.91	737.51	123.05	83.3	84.3	4.3
openA-2	53.9	52.1	20.3	1.23	1.2	0.41	11.95	7.74	31.79	88.05	92.26	68.21	668.92	126.16	81.1	82.2	9.7
openA-3	50.5	66.4	1.9	1.22	0.83	1.99	11.46	8.82	52.06	88.54	91.18	47.94	655.91	120.57	81.6	83.6	3.3
openA-4	50.2	51.7	17.1	1.26	1.17	0.34	11.08	8.09	41.17	88.92	91.91	58.83	773.87	118.95	84.6	85.3	6.1
openA-5	52.1	66.1	3.8	1.24	0.89	1.31	10.51	7.84	53.2	89.49	92.16	46.8	763.84	124	83.8	85.2	4.0
openA-6	107.5	116.6	8.8	1.28	1.14	0.77	13.8	10.61	50.66	86.2	89.39	49.34	815.96	148.61	81.8	82.4	2.8
openA-7	61.3	69.8	9.7	1.23	1.03	0.42	12.5	10.11	50.98	87.5	89.89	49.02	765.38	148.16	80.6	81.5	3.0
openA-8	33.8	39.1	12.4	1.28	0.84	0.27	12.5	8.89	50.9	87.5	91.11	49.1	835.21	146.82	82.4	86.7	4.3
openA-9	78.1	87.3	9.3	1.32	1.13	0.53	11.38	9.14	47.54	88.62	90.86	52.46	747.27	151.78	79.7	80.6	2.8
openA-10	47	53.7	11	1.26	0.97	0.35	11.24	7.81	48.6	88.76	92.19	51.4	668.81	138.54	79.3	81.8	3.8
openA-11	52.9	63.8	6.7	1.14	0.87	0.51	11.74	8.35	54.45	88.26	91.65	45.55	708.26	152.33	78.5	80.2	2.9
openA-12	59.2	70.6	6.7	1.13	0.85	0.41	11.67	8.16	53.58	88.33	91.84	46.42	707.32	149.96	78.8	81.0	2.2
openA-13	60.2	67.9	8.8	1.13	0.9	0.47	10.8	8.54	50.03	89.2	91.46	49.97	752.83	152.55	79.7	81.8	3.4
openA-14	50.3	66.8	4.5	1.15	0.83	0.67	11.25	8.33	50.96	88.75	91.67	49.04	758.01	149.32	80.3	81.1	2.9
openA-15	44.9	66.2	7.5	1.14	0.73	0.41	10.78	7.58	51.99	89.22	92.42	48.01	749.72	143.34	80.9	81.9	3.2
openA-16	68.2	65.9	2.8	1.15	1	1.57	11.11	8.78	46.95	88.89	91.22	53.05	697.18	145.89	79.1	82.4	3.3
openA-17	67.4	66.2	1.1	1.12	1.02	3.91	10.9	8.74	43.79	89.1	91.26	56.21	753.31	141.04	81.3	83.3	3.6
openA-18	47.8	61.4	4.6	1.35	0.97	0.37	11.19	8.18	53.18	88.81	91.82	46.82	838.95	160.66	80.8	82.3	1.4
openA-19	46.1	58.8	5.2	1.36	0.97	0.4	11.1	8.15	54.01	88.9	91.85	45.99	922.38	164.88	82.1	83.7	1.7
openA-20	46.1	60.1	4	1.23	0.92	0.43	10.57	8.59	51.56	89.43	91.41	48.44	928.25	165.96	82.1	82.6	1.6
openA-21	46	58.9	4.9	1.28	0.9	0.36	10.09	8.34	51.07	89.91	91.66	48.93	801.86	145.32	81.9	83.7	1.6
openB-1	54.2	72.2	1.2	1.2	0.87	1.07	10.4	9.08	47.93	89.6	90.92	52.07	853.5	430.15	49.6	51.3	1.1
openB-2	54.4	72.6	0.6	1.16	0.88	0.35	9.63	10.4	44.7	90.37	89.6	55.3	901.71	642.13	28.8	27.9	0.2
openB-3	59.1	74.9	3.3	1.2	0.91	0.7	9.94	7.88	48.72	90.06	92.12	51.28	847.75	292.49	65.5	66.8	1.9
openB-4	63.8	76.1	6.9	1.18	0.92	0.54	10.24	7.85	46.74	89.76	92.15	53.26	849.45	247.51	70.9	72.9	2.9
openB-5	57.5	73.6	3.4	1.2	0.88	0.57	9.69	8.36	48.58	90.31	91.64	51.42	779.55	269.2	65.5	67.6	1.6
openB-7	61.3	79.5	0.8	1.16	0.92	4.19	11.92	11.29	41.16	88.08	88.71	58.84	767.11	301.76	60.7	59.5	3.1
openB-8	29.1	47.3	1.1	1.14	0.88	3.58	11.51	9.6	43.94	88.49	90.4	56.06	833.62	236.76	71.6	64.4	7.5
openB-9	104.7	122.6	1.4	1.21	0.96	2.48	12.61	12.55	43.34	87.39	87.45	56.66	853.3	408.18	52.2	55.6	1.8
openB-10	54.3	71.7	1.2	1.15	0.87	4.2	11.67	10.96	45.83	88.33	89.04	54.17	835.36	311.06	62.8	62.8	4.9
openB-11	21.4	38.8	1.8	1.21	0.68	3.62	11.97	10.25	47.11	88.03	89.75	52.89	849	285.86	66.3	65.7	15.1
openB-12	73.3	90.8	1.3	1.2	0.97	1.8	12.15	10.87	43.81	87.85	89.13	56.19	864.99	428.86	50.4	50.4	1.7
openB-13	36.5	54	1.8	1.25	0.8	1.13	11.76	10.17	46.02	88.24	89.83	53.98	836.31	311.31	62.8	64.8	2.7
openB-14	40.4	55	3	1.32	0.89	0.38	11.73	9.9	49.05	88.27	90.1	50.95	894.23	249.89	72.1	74.3	1.2
openB-15	39.7	53.7	3.6	1.33	0.9	0.39	11.16	9.73	48.58	88.84	90.27	51.42	867.81	249.28	71.3	73.7	1.5
openB-16	39.2	53.3	3.6	1.34	0.92	0.28	10.32	8.94	47.76	89.68	91.06	52.24	822.06	236.6	71.2	73.1	1.1
openB-17	41.3	55	3.8	1.36	0.91	0.32	9.87	8.63	46.24	90.13	91.37	53.76	886.34	224.48	74.7	77.4	1.3
openB-18	40.5	51.5	6.6	1.3	0.81	0.17	11.6	9.16	49.5	88.4	90.84	50.5	826.17	197.81	76.1	81.0	1.2
openB-19	43.5	55.1	5.7	1.36	0.92	0.31	12.24	10.16	47.78	87.76	89.84	52.22	965.06	221.95	77.0	80.3	1.8
openB-20	36.4	49.1	4.8	1.42	0.99	0.45	12.66	10.05	52.55	87.34	89.95	47.45	902.45	234.45	74.0	75.6	2.3
openB-21	35.7	47.8	5.6	1.42	0.93	0.42	13.72	10.62	53.25	86.28	89.38	46.75	986.25	227.85	76.9	79.7	2.5