Antti Haapala

PAPER MACHINE WHITE WATER TREATMENT IN CHANNEL FLOW

INTEGRATION OF PASSIVE DEAERATION AND SELECTIVE FLOTATION
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Integration of passive deaeration and selective flotation

Academic dissertation to be presented with the assent of the Faculty of Technology of the University of Oulu for public defence in Auditorium TA105, Linnanmaa, on 10 December 2010, at 12 noon

UNIVERSITY OF OULU, OULU 2010
Abstract

Gas removal from the papermaking process is currently a standard practice, whereas purification of the internal water circulation has become common only recently. Both unit processes have progressed greatly during recent decades and new concepts are constantly being developed. The aim of this thesis was to analyse the efficiency and applicability of a channel flow design introduced by Metso for passive white water deaeration and to study the dynamics of passive bubbly gas removal. In addition, separation of the detrimental process water components by selective flotation during deaeration was studied to add further functionality to the channel flow design.

Turbulent mixing at the flow discharge and the consequent air entrainment were seen to limit the gas separation efficiency. Also, the properties of different white waters notably affect their deaeration through viscous forces, the concentration of surface active components and bubble-particle interactions. Thus similar levels of gas separation cannot be achieved with all process waters. The analysis showed that the drag of small microbubbles is mostly caused by hydrophobic contamination and the dispersed particles that readily attach to the bubbles. Correlations were derived based on experimental data to provide new information on the drag force experienced by small bubbles in white waters.

Chemically unaided flotation of white water in the channel flow was shown to be efficient in separating hydrophobic contaminants that have adverse effects on paper machine production and product quality. Both good reductions in contaminant content and high selectivity in their removal were achieved. Channel flow with an overflow can be considered well suited for the first stage of froth separation, while further treatment of the channel flow reject may consist of a secondary flotation or other process that enables the recirculation of fines and fillers. Although a certain level of losses of fines and fillers must be expected, substantial fraction of these solid components can be returned to the process stream.

The proposed multifunctional process, channel flow deaeration and frothing of white water, was seen to be straightforward, economical and feasible while also providing benefits in terms of total process efficiency that are not delivered by any current process scheme. The experimental parameters presented here regarding bubble dynamics and flotation efficiency can be used to achieve better models of these processes.

Keywords: air content, air entrainment, bubbles, contaminants, deaeration, drag, flotation, gas content measurement, gas separation, wet end, white water
Acknowledgements

The research work for this thesis was carried out in the Fibre and particle engineering laboratory at the University of Oulu during the years 2006–2010 in co-operation with the International Doctoral Programme in Pulp and Paper Science and Technology (PaPSaT). The work was financed by the Ministry of Education, the Finnish Funding Agency for Technology and Innovation (TEKES), Metso Paper, The Finnish Cultural Foundation’s Kainuu Regional Fund, Finnish Foundation for Technology Promotion, Finnish Society of Automation, Oulu University Scholarship Foundation and Tauno Tönninki Foundation – support from all sources is gratefully acknowledged in these trying times.

I wish to thank my supervisor Professor Jouko Niinimäki for his guidance and the opportunity to work on this thesis. I am also grateful to Dr Tuomas Stoor for the valuable advices and the countless discussions during these years. Official reviewers of this thesis, Professor Martin Hubbe from North Carolina State University and Professor Pentti Saarenrinne from Tampere University of Technology are greatly appreciated for their efforts and valuable commentary on the manuscript of this thesis. Sincere thanks also to Malcolm Hicks for revising the English language of the manuscript. I also wish to thank all the co-authors for their valued contribution on all the jointly drafted articles during these few years.

I would like to thank my colleagues, friends and technical personnel at the Fibre and Particle Engineering Laboratory and the workshop of our department. The work provided by Ari, Pablo, Sakari, Sanna and Topi during some of the trials proved priceless. Similarly those involved in projects that helped to forge this thesis deserve warm thanks – especially Arto, Markus and Sanna from MUSCA and Juan, Lefa and Sami from Metso Inc.

Special thanks go to Henrikki, Kalle, Mikko K., Mikko N. and Tommi of the notorious “Elämysmatkailijat” group for many interesting bonding experiences in the Finnish wilderness, wide-ranging discussions and unforgettable friendship also outside the office hours. Mika, Ossi and Pasi – your input and help on many things is also highly appreciated. Also, without the patience and goodwill of Sami I might still struggle with the tortuous test setup designs and build-ups.

Finally I wish to thank my parents, relatives and dear friends near and far. Your support and encouragement has helped me to decisively pull this through.

Oulu, November 2010

Antti Haapala
### List of abbreviations and symbols

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>CFD</td>
<td>Computational fluid dynamics</td>
</tr>
<tr>
<td>CMC</td>
<td>Carboxymethyl cellulose</td>
</tr>
<tr>
<td>CMOS</td>
<td>Complementary metal oxide semiconductor</td>
</tr>
<tr>
<td>DAF</td>
<td>Dissolved air flotation</td>
</tr>
<tr>
<td>DCS</td>
<td>Dissolved and colloidal substances</td>
</tr>
<tr>
<td>DI</td>
<td>Direct imaging</td>
</tr>
<tr>
<td>DIP</td>
<td>Deinked pulp</td>
</tr>
<tr>
<td>DMC</td>
<td>Dry matter content</td>
</tr>
<tr>
<td>DNA</td>
<td>Deoxyribonucleic acid</td>
</tr>
<tr>
<td>EFD</td>
<td>Experimental fluid dynamics</td>
</tr>
<tr>
<td>ELS</td>
<td>Evaporative light scattering</td>
</tr>
<tr>
<td>GCC</td>
<td>Ground calcium carbonate</td>
</tr>
<tr>
<td>GW</td>
<td>Groundwood pulp</td>
</tr>
<tr>
<td>HPLC</td>
<td>High precision liquid chromatography</td>
</tr>
<tr>
<td>MTBE</td>
<td>Methyl tert-butyl ether</td>
</tr>
<tr>
<td>MP</td>
<td>Mechanical pulp</td>
</tr>
<tr>
<td>OCC</td>
<td>Old corrugated container pulp</td>
</tr>
<tr>
<td>PCC</td>
<td>Precipitated calcium carbonate</td>
</tr>
<tr>
<td>PCR</td>
<td>Polymerase chain reaction</td>
</tr>
<tr>
<td>PGW</td>
<td>Pressurised groundwood pulp</td>
</tr>
<tr>
<td>POMp</td>
<td>Degassing pump from POM Technologies</td>
</tr>
<tr>
<td>PUD</td>
<td>Pulsed ultrasound Doppler</td>
</tr>
<tr>
<td>RCF</td>
<td>Recycled cellulose fibre</td>
</tr>
<tr>
<td>SEC</td>
<td>Size-exclusion column</td>
</tr>
<tr>
<td>THF</td>
<td>Tetrahydrofuran</td>
</tr>
<tr>
<td>TMP</td>
<td>Thermomechanical pulp</td>
</tr>
<tr>
<td>VTT</td>
<td>Technical Research Centre of Finland</td>
</tr>
<tr>
<td>WW</td>
<td>White water</td>
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</tbody>
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\[
\begin{align*}
A & \text{ area of flow cross section } [m^2] \\
A_B & \text{ surface area of a bubble } [m^2] \\
C_D & \text{ drag coefficient } [-] \\
d_B & \text{ diameter of a bubble } [m] \\
E_r & \text{ efficiency of removal } [-] \\
L & \text{ characteristic length scale } [m]
\end{align*}
\]
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
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<tbody>
<tr>
<td>$m$</td>
<td>mass</td>
<td>[kg]</td>
</tr>
<tr>
<td>$\dot{m}$</td>
<td>mass flow rate</td>
<td>[g/s]</td>
</tr>
<tr>
<td>$Q$</td>
<td>volume rate of flow</td>
<td>[m$^3$/s]</td>
</tr>
<tr>
<td>$Q_N$</td>
<td>Nelson’s selectivity Q-index</td>
<td>[-]</td>
</tr>
<tr>
<td>$r$</td>
<td>bubble radius</td>
<td>[m]</td>
</tr>
<tr>
<td>$Re$</td>
<td>Reynolds number for flow</td>
<td>[-]</td>
</tr>
<tr>
<td>$Re_B$</td>
<td>Reynolds number for a bubble</td>
<td>[-]</td>
</tr>
<tr>
<td>$RR_m$</td>
<td>reject rate by mass</td>
<td>[-]</td>
</tr>
<tr>
<td>$RR_V$</td>
<td>reject rate by volume</td>
<td>[-]</td>
</tr>
<tr>
<td>$U$</td>
<td>characteristic flow velocity</td>
<td>[m/s]</td>
</tr>
<tr>
<td>$U_B$</td>
<td>velocity of a bubble</td>
<td>[m/s]</td>
</tr>
<tr>
<td>$U_L$</td>
<td>fluid velocity</td>
<td>[m/s]</td>
</tr>
<tr>
<td>$v$</td>
<td>average fluid velocity</td>
<td>[m/s]</td>
</tr>
<tr>
<td>$V_B$</td>
<td>volume of a bubble</td>
<td>[m$^3$]</td>
</tr>
<tr>
<td>$x$</td>
<td>concentration of a given component</td>
<td>[%]</td>
</tr>
<tr>
<td>$\mu$</td>
<td>dynamic fluid viscosity</td>
<td>[Pa·s]</td>
</tr>
<tr>
<td>$\nu_L$</td>
<td>kinematic fluid viscosity</td>
<td>[m$^2$/s]</td>
</tr>
<tr>
<td>$\rho$</td>
<td>fluid density</td>
<td>[kg/m$^3$]</td>
</tr>
<tr>
<td>$\rho_B$</td>
<td>gas density of a bubble</td>
<td>[kg/m$^3$]</td>
</tr>
<tr>
<td>$\rho_L$</td>
<td>liquid phase density</td>
<td>[kg/m$^3$]</td>
</tr>
</tbody>
</table>
List of original papers

This thesis is based on the following papers, which are referred throughout the text by their Roman numerals:


The present author was the principal author of all the papers, with the main responsibility for the experimental design and realization, analysis and reporting of the results. The results were also partly analysed and reported by the second author in Paper II, the fourth author in Paper III and the second and fourth authors in Paper IV. The other co-authors participated in the experimental design and writing of the papers.

Other related publications by author


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1 Introduction

1.1 Background

The dual nature of gases in papermaking operations is well known. On the one hand, gases perform several essential tasks and can be considered beneficial. In pulping and effluent treatment bubbly gases are utilised mostly in flotation, bleaching and bacteria control operations. In the proximity of a paper or board machine, however, gas bubbles are primarily viewed as detrimental to pumping efficiency and measurement accuracy (Stoor et al. 2000, 2005). They are also seen to promote deposition of contaminants and to have an adverse effect on many end product properties. In addition, gases become contaminants in themselves in certain stages of the process (De Cew 1935, Helle et al. 2000).

Early papermaking processes managed deaeration by means of wire pits and open tanks, and actual deaeration processes were introduced only during the 1950’s (Smith 1952), when the flotation deinking scheme was also adopted from the mineral processing industry for the cleaning of recycled pulp (Finch & Hardie 1999). Processes have since been developed for deaerating the water and pulp suspensions separately from those designed to feed air in and promote foam formation. While the old open vessel deaeration system remains in use in many older paper machines, it is scarcely used in new paper machine installations, due to the rapid pace of the water and pulp flows. Instead, deaeration is often achieved by combinations of vacuum tanks, gas removing pumps or hydrocyclones, and promoted by chemical means (Stoor 2000, Helle 2007). Similarly, flotation applications are not commonly used to purify the closed internal flow loops of newer paper machines, a function that is commonly performed by other means, e.g. membrane filtration, chemical or biological treatments (Hubbe 2007b).

Lack of time and space within the hectic process at the paper machine wet end has also had the effect that the deaeration and water purification processes have not thus far been intentionally combined. Some limitations governing these paradigms can be overcome, however, by employing a different flow geometry instead of the traditional pipeline, tank or chest. This thesis involves an evaluation of a technology of a channel flow design introduced in the late 1990s by Metso that can replace the traditional wire pit design for collecting and deaerating the white water, i.e. the head box furnish filtrate from the wire section (Ahola et al.
The flow channel can be considered as a substantially extended white water tray in comparison to modern wet end designs. Channel flow provides a short route for the evacuation of bubbles and in many cases ensures the residence time needed for the flow to deaerate down to a reasonable level. In addition to its deaeration abilities, the channel flow concept also enables froth build-up and removal from the white water circulation. Such a novel design in the somewhat traditional wet end configuration nevertheless raises new process design challenges, primarily minimisation of the vessel dimensions and estimation of the required bubble rise timescale. These issues are challenging and often case-sensitive ones, but fortunately the tools available for studying complex flows have been greatly upgraded in recent years.

The processes of deaeration of a suspension through buoyant bubble rise and purification of water by flotation are both based on the same fundamental phenomena of suspension flows, the buoyancy of floating bodies and the surface forces prevailing at different phases. It is well established that the use of numerical tools, i.e. computational fluid dynamics (CFD), can make the description of complicated flows possible. The limitations of CFD methods, e.g. related to the speed of the available computers, will continue to exist for a long time, and so a number of components can only be investigated reliably by the methods of experimental fluid dynamics (EFD). Since not all the quantities of interest from a fluid mechanics point of view can be determined, experimental studies serve to provide vital insights into the complex phenomena, which can then be approximated and modelled by numerical tools available for various engineering purposes.

This study focuses on phenomena related to microbubble rise and deaeration in an open channel flow of paper machine white water, and to the ability of the bubbles to form froth and remove detrimental hydrophobic materials from the water circulation. The objective was to determine how well a channel flow process can manage its function of white water deaeration with a further task of water purification by frothing, and what are the crucial parameters governing the efficiency of its operation. The work was conducted experimentally using paper and board mill white water in different experimental setups to define the essential parameters and data to support CFD flow simulations for use in process design.
1.2 The research problem

Deaeration of paper machine furnishes and circulating water is commonly achieved mechanically in a de-pressurised deaeration tank, by means of gas removing pumps or various cyclone technologies, or via chemical treatments. Thus the possibilities for utilising the inherent tendency of buoyant bubbles to rise as a means of process water deaeration in a channel flow setup represent a recent process concept, with the addition of an integrated white water flotation function, and certain issues relating to the dynamics of bubble motion in these multiphase suspensions remain unclear. In addition, bubbly gases in paper machine suspensions tend to induce foaming, but the beneficial effects to be achieved by froth removal have not been thoroughly investigated, as it has been common practice to reduce froth formation by chemical means.

1.3 The aim and hypotheses

The aim of this thesis was to ascertain the extent to which entrained gases can be removed from white water in an open channel flow without external energy consumption and to quantify the rate of bubble rise, its limiting factors and its overall applicability. Also to be investigated was the applicability of froth removal from channel flow in order to purify the circulation water. The following hypotheses regarding the phenomena of gas separation and frothing were posited and tested in order to solve the above research problem:

1. Sufficient gas separation can be obtained within a reasonable residence time when a channel flow configuration is used instead of a traditional wire pit (Paper I, Haapala et al. (2008, 2010a), Laari et al. (2007, 2010)). The rise of bubbly gases is hindered in process water to an extent that needs to be considered in the designing and dimensioning of industrial channel flow deaeration processes (Paper II).

2. Circulation water purification would benefit paper machine runnability, increase the available production time and improve certain common paper quality issues (Paper III). The flow channel used for deaeration purposes can act as a flotation vessel for removing hydrophobic contaminants that become concentrated in the short circulation (Paper IV, Haapala et al. (2010a)).
1.4 Outline of the thesis

This thesis is organised around two individual unit operations, namely the passive deaeration of white water in an open channel flow and white water purification by means of froth flotation. As an outcome, the thesis combines the benefits offered by these by forming them into a single multi-functional process of deaeration and water purification by flotation.

The first chapter of this thesis describes the problem to be investigated, states the hypotheses and presents the aim and an outline of the work. The second chapter will introduce the development of the relevant paper machine short circulation operations and their state-of-the-art technologies, and will outline the background to this thesis. The third chapter will introduce the environments, materials and analyses used in the experimental work.

The fourth chapter will present the results with respect to open channel flow deaeration and microbubble dynamics (hypothesis 1). It will also discuss the composition and flow behaviour of white water, illustrate the importance of dispersed phase particles and describe the relevant physico-chemical properties and flow dynamics related to buoyancy-driven gas removal.

The fifth chapter will contain the results regarding the flotation purification of white water, with a discussion of efficiency and selectivity issues with regard to the removal of detrimental substances, including losses of beneficial fibre and mineral fines (hypothesis 2). The laboratory experiments are discussed in parallel with the analysis of a pilot scale process in which channel flow is used for deaeration and white water frothing.

The sixth chapter will present practical conclusions based on the most important findings of the thesis and consider prospects for future studies. Outline of the thesis based on the original scientific publications is provided in Fig. 1.
Paper machine white water treatment in channel flow. Integration of passive deaeration and selective flotation

Passive white water deaeration
- Measurement of bubbly gases from process water flow (Haapala et al. 2006)
- Microlbubble hydrodynamics in process waters (Paper II)

White water purification
- Contaminants in circulation waters and their effect on papermaking (Paper III and Haapala et al. 2009, 2010b)
- Contaminant removal from process waters by flotation (Paper IV)
- White water purification by a two-stage flotation arrangement (Haapala et al. 2010a)

Fig. 1. Outline of the thesis.
2 Development of paper machine wet end unit operations

Gas removal from the papermaking process is currently a standard practice, whereas purification of the internal water circulation has become common only during the past few years. Both unit processes have progressed greatly in recent decades and new concepts aimed at higher performance and lower operational costs are constantly being developed.

In order to appreciate the technological advances made in these areas, it is beneficial to understand the historical background to paper machine wet end development. The demands and preconditions set by process economics, energy use, environmental issues and product quality, for instance, have led to constant adaptation of the process designs. The following sections present the development of the paper machine wet end, our present understanding of its functioning and especially the deaeration and internal water purification technologies relevant to this thesis.

2.1 Development of paper machine and wet end design

The Fourdrinier Brothers’ papermaking machines installed in Hertfordshire, England, in 1803 and 1804 are considered today to mark the start of modern papermaking. At this early stage the paper sheet was air-dried and production powered by steam or water wheels, thus differentiating it from modern machines, but the construction and overall lay-out of the machines have remained remarkably similar up to modern times (Hunter 1978, Nykänen 2005). Flat-type and cylinder machines gained ground in the early 19th century and were extended to include a dryer section and a reeler, and also a calender section around the 1850s (Holik 2006). These early designs also had open containers for pulp and waters that acted as rudimentary deaeration devices, although not specifically designed for this function.

These paper machine designs were followed by a period of rapid development in all sectors of papermaking (Holik 2006). As a result of a wide array of innovations in engineering, the web width of paper machines was enlarged, working speeds increased considerably and multicylinder machines were designed specifically for the production of particular grades of paper and board (Nykänen 2005). These modern paper mill constructions were larger in wet
end volume but nevertheless still based on the Fourdrinier single wire machine as it emerged after the Second World War.

Even when these modern paper machines were built on a larger scale, the components used in stock preparation and in the paper machines themselves, including wet end operations, the approach flow and the headbox, were for a long time quite rudimentary. The common unit operations that we associate today with the short circulation and approach flow – cleaning, screening and deaeration – were not present as such in the early machines. Mesh screens were introduced in the 1860’s, the first pressure screens with a similar construction to those in use today were commercialised in the early 1950’s (Young 1983) and it was around that time, too, that hydrocyclone cleaners (Bliss 1994) and the first vacuum deaeration tanks, or deculators, came into wider use (Smith 1952). These, and other deaeration related unit operation development steps are reviewed in detail in the subsequent chapter.

The emergence of new process equipment and the need for higher production rates acted hand-in-hand with the development of the lay-out structure of the paper machine wet end and approach flow. Novel unit operations, e.g. for screening and cleaning, and larger flow volumes initially provided higher quality and better stability of operation. During the 1980s it became apparent that while a conventional, fixed lay-out structure with large volumes provided economic benefits of scale, the processes were cumbersome. The basic problem in the optimisation process was the large volumes of stock in the papermaking process: every change of grade in the process affected everything else, and it took a long time to balance the stock in the process. Until the 1990s practically all paper machines operated in a similar fashion with regard to their stock preparation and wet end processes. There were no viable options, as the evolution of technology had driven all machine manufacturers to view the process more or less similarly. In order to shift towards more flexible production, the volumes of stock used in the process had to be minimised (Hyvönen 2005, Nykänen 2005).

Consequently, the latest developments in short circulation design have come in the form of compact papermaking platforms. These aim at minimising the short circulation volume, turnaround time and control delay associated with grade changes while also paying special attention to process stability, mixing and deaeration processes. At the same time the need for faster response times and a simple, cost-effective process design has been emphasized. It was the streamlined design concepts first presented by Meinander (1993) that started the trend of compact papermaking in 1996 (Meinander & Olsson 1999). The Metso company
was already developing its version of a new short circulation concept at that time, which was eventually introduced in 1998 (Ahola et al. 2002, Grön & Ahola 2003). This relied on similar ideas of simplification and fast response, with white-water deaeration taking place in a vacuum tank in the faster machines and passive gas removal with a passive channel flow solution to replace the wire pit in slower machines. Voith soon responded to this novel ideology by introducing its own concept in 2000, with stock deaeration only at machine speeds of over 1000 m/s (Schwarz & Gmeiner 2000, Gommel & Kohrs 2003), and Andritz also launched a similar wet end process with reduced flow volumes and a simplified layout (Matula 2000, Matula & Parviainen 2001).

From a technological point of view the basic idea in all these concepts is to simplify the wet end. The main difference between the concepts, as noted by Lahti (2005), lies in where and how the deaeration is performed. Especially the need for complete gas removal and the question of an acceptable gas content for undisturbed papermaking have been under debate in recent years. Traditionally, the layout has highlighted the importance of complete stock and white water deaeration in the short circulation, but the trend recently has been towards only white water deaeration (Stoor 2006).

Where deaeration is performed on the whole of the head box stock in the Andritz concept, it applies to only the white water in POM Technologies’ system, while both alternatives are possible in the Metso and Voith systems. Also, it is apparent that combinations of novel and conventional technologies are possible with all the new designs and that future rebuilds will probably include standalone installations of mixing, cleaning and deaeration unit operations alongside conventional wet end unit processes. It is also likely that the screening and internal purification processes will see further development as priority is given to machine runnability and water usage (Callaway 1994).

### 2.2 Deaeration unit operations

During the first 150 years of mechanized paper manufacturing there was no need for a unit process that would extract gases from stock or circulation water, as the speeds at which machines operated gave the stock ample residence time in the open tanks, chests and chutes during which deaeration could take place. The connection between gases in the stock and problems such as slow filtration and pinhole formation had not been established, and hence the presence of gases in the suspensions was not considered an issue for the papermaking process.
The first observations concerning the behaviour of bubbles in fibre suspensions were reported by De Cew (1929, 1930, 1935), who stated that air on the dried fibres has a stronger affinity for these fibres than for the water, and therefore the fibres must be beaten within the water to dislodge the gas in the form of fine particles, which may escape if they do not dissolve. Actual development of the stock deaeration process began in the late 1940s, following the introduction of the pressurized head box and the quest for higher paper machine speeds.

By that time sheet formation was being impaired by entrained air bubbles that were noted to create pinholes and micro-scale flocculation. To address these air entrainment problems, the Clark & Vicario Corp. introduced its Deculator™ process, named after De Cew, which embraced the principle of vacuum deaeration of the entire stock flow prior to the head box (Smith 1952). This work was continued in the 1950’s by Goumeniouk (1954) and Boadway (1956), among others, who studied the behaviour of gases in the head box and on the wire. At the same time it became apparent that the best way to reduce gas-related problems was to minimize the entrainment and mixing of gases into the process. A consensus over this issue was reached in the 1950’s, when the air entrainment problem was studied intensively in the USA, Canada and Germany. Process design considerations had to be extended throughout the fibre line, taking into consideration the pump suction piping, inlet piping, tank and mixer pressurizing, sealing, dimensioning and positioning, etc. The fundamental considerations when designing a gas-resistant pulp or paper mill were clarified during the following years, and they have subsequently been discussed in detail by Ewald & Rippl (1982), Pantaleo (1991) and Messenger (1997).

The Deculator was soon challenged by other similar systems, and trade names such as Ensovac and Perivac were introduced. Yet all the above make use of the same overall construction and basis of operation as “the original” Deculator system. In some designs the vacuum tank is also equipped with an integrated cleaner system in which the accept from the centrifugal cleaner is discharged into the vacuum (Jacobsson 1958, 1969), and more recently the integration of gas removal into the sand removal procedure effected by hydrocyclone cleaners has also been investigated in the short circulation of a paper machine by CFD modelling, as presented by Narasimha et al. (2006) and in the experimental work reported by Jokinen et al. (2007).

Innovations relating to the use of centrifugal forces to deaerate stock and water have led to gas-removing pumps and mixer designs scattered throughout
the wet end rather than focusing deaeration on any single location or process. The whole POM Technologies concept of papermaking as devised by Meinander (1993, 2003, 2005) has been built up on this idea of continuous gas content management, and as such it represents some of the latest developments in the field of gas separation. Additional energy consumption is needed to maintain the centrifugal forces, however, and this remains the main disadvantage of vortex technology similar to hydrocyclones. To minimize energy consumption and still achieve reasonable gas removal, Metso came up with the OptiAir Flume flow channel in the late 1990s to replace the traditional wire pit design for collecting the filtrate water draining from a wet sheet of paper as it is being formed (Ahola et al. 2002). The CFD modelling approach for investigating the efficiency of channel flow deaeration has been presented by Laari et al. (2007, 2010). Models without experimental validation and parameters remain rudimentary, however, and their use in engineering tools requires a high level of accuracy. The experimental work contained in this thesis aims to provide these necessary experimental coefficients and to provide validation data for CFD models. Practicable conditions for this and the efficiency of buoyant passive deaeration of a channel flow process are considered in the Paper I and in Haapala et al. (2008, 2010a), while Paper II provides insights into the dynamics of microbubbles in white water.

### 2.3 The present understanding of wet end deaeration

The wet end of a paper machine is designed to perform its functions of furnish preparation and cleaning prior to the approach flow to the head box. One of the challenges faced by designers today is to minimise gas entrainment at this point. Many ideas have been introduced for eliminating gas entrainment and removing gases from these processes, as discussed earlier, and the trend has recently been away from total deaeration and towards decentralized systems and white water deaeration.

It has been noted in the recent studies of Helle (2000), Rauch & Sangl (2000), Stoor et al. (2000), Helle & Paulapuro (2004), Lamminen (2004) and Stoor et al. (2005), for example, that the detrimental effects of gases arise from the entrained or bubbly gas content of the flow and that the dissolved gas is not actively involved in the papermaking process, as long as it stays in dissolved form. However, dissolved gases are readily converted to gaseous form when conditions such as pressure change. Typically bubbles are precipitated from dissolved gases
at the moment when the headbox pressure is released when the stock comes out of
the slice, so high content of dissolved gas can reduce drainage and formation on
the wire section (Matula & Kukkamäki 1998, Stoor 2006, Helle 2007). Dissolved
gases in closed circulation oxidise substances in the circulation and prevents the
growth of anaerobic bacteria in the system (Woodward 1996). Hence, as noted by
Helle (2007), dissolved gas removal is not necessary for papermaking, provided
that the process is correctly designed. This has led to a discussion on the
acceptable bubbly gas content of the wet end that would both enable trouble-free,
high quality production and minimise the costs of deaeration (Stoor 2006, Helle
2007).

Despite the many investigations, the findings on the subject remain case-
sensitive and generalisations are difficult to make. Broadly speaking, it has been
noted that liner and board machines can be fairly tolerant of entrained gas
contents from 0.5% up to 2.5%, whereas some properties of low grammage paper
products may already suffer from a gas content of 0.1–0.4% in the head box flow

A high entrained gas content in the wet end can be detrimental, and the
qualitative effects of entrained gases are well known. These effects can often be
coped with, and depending on the paper process, they may not hinder efficiency
in any practical way. Hence the question becomes one of how to achieve a “good
enough” gas content in the wet end at the minimal total cost, taking into account
the installation, maintenance and daily operation of the deaeration system.

The cheapest possible method would be a passive mechanical deaeration that
requires no external energy or use of chemicals, but no such system has been
actively pursued since the introduction of vacuum deaeration at the point when
open tanks and wire pits were considered ineffective. These methods have
recently been introduced, however, within the concepts of off-machine silos
(Matula & Parviainen 2001) and flow channels or flumes (Ahola et al. 2002).
Deaeration in such systems is dependent on the buoyant rise velocity of the
bubbles in the process suspensions, the distance they have to rise in order to
evacuate and the residence time of the flow, as provided by the vessel
dimensioning. Calculation of the bubble kinetics in the case of a pure liquid and a
stagnant or laminar flow are quite straightforward, but given a turbulent, multi-
phase flow with a wide distribution of bubbles, some experimental work is
required.
2.4 Development of water usage and internal water purification

The manufacture of paper products requires large amounts of process water. Before water consumption came to be limited by environmental constraints from the 1970s onwards, the process water consisted mainly of incoming fresh water that was discharged as waste water after the production process. Early in the twentieth century it was common for a paper machine system to use 500 to 1000 m$^3$ of fresh water per tonne of product and then dump the excess water directly into a lake or river (Hamm & Göttscning 2002), but by the 1960s the average water consumption had dropped to 240 m$^3$/t and this gradually decreased further over the years to around 10 m$^3$/t in the 1990s (Huster et al., 1991, Edde 1994).

The proposed solution for reducing the use of water was either purification of the pulp and fresh water or closure of the water system, which would reduce the amount of waste water practically to zero and require an input of fresh water only to compensate for evaporative water losses (Brecht et al. 1974). Pulp washing and flotation treatments were known to reduce the contaminant load (e.g. Brune 1917), but complete cleaning of the pulp was not attainable. Partial closure of the water circulation offered substantial benefits, however, such as no charges for effluent discharge, less dependence on fresh water and its purification, and also a reduction in energy consumption, as closed systems have less cold fresh water to heat to the process temperature (Habets & Knelissen 1997).

Practical experience, however, soon revealed several problems associated with entirely closed water systems, mostly caused either directly or indirectly by the various components of the white water that would have been removed with the effluent in an open water system. Increasing concentrations of inorganic and organic substances were noted to cause a loss of production and to have deleterious effects on product quality, as can also be seen in modern processes (Göttscning & Dalpke 1976, Roism 1990, Landry 1997, Uesaka et al. 2001, Sawamura 2003, Haapala et al. 2010b). The decline in water quality caused operational problems such as plugging of screens and showers, serious corrosion (Streebin et al. 1976) and paper quality defects related to large quantities of microorganisms (Jung & Kutzner 1978). The presence of various contaminants has been connected with runnability difficulties in paper production, and connections have also been proposed recently between web defect formation, web breakage, wet end contamination and various sources of contamination (Roism 1990l, Uesaka 2001, Haapala 2005). These adverse effects of pitch and other wet
end contaminants in a closed loop paper production have also been studied in Paper III of this thesis.

Due to the diversity of paper processes, the composition of the contaminants and their adverse effects on process operations and product quality are hard to quantify with certainty, as the process chemistry is very variable (Alexandersson 2003, Hubbe et al. 2006). Organic contaminants are often considered more detrimental than inorganic ones, having a higher propensity for forming tacky agglomerates. One commonly used classification for organic contaminants is that proposed by Putz (2000), as in Fig. 2.

![Fig. 2. Contaminants frequently identified in paper machine deposits from recovered paper processing mills. (Putz 2000, © The Finnish Paper Engineers' Association).](image)

When the concentration of a component exceeds its solubility level, it forms aggregates or comes in contact with a surface to which it may attach itself, causing white water components to become enriched in the macroscopic layer deposits. The deposition tendency of solid contaminants is reduced by steric stabilization of components, i.e. formation of protective layer from soluble substances around the particles. On the other hand, rapid changes in the system’s chemical conditions, such as pH, temperature or electrolyte concentration, can reduce the charge and stability of particles and lead to severe deposition problems.

Deposits of a tacky nature composed of calcium carbonate, various hydrophobic agents and microbes are often found on equipment surfaces, for example (Kallio 2007; Hubbe et al. 2006). It is also very common for the deposits to be composed of a mixture of substances, without the enrichment of any
particular component, e.g. pitch droplets covered by microbes (Lindberg et al. 2004), wood resin that increases the depositional tendency of white pitch (Vähäsalmo 2005), or microbes attached to surfaces so that they can collect fibres, fillers and detrimental components on their tacky biofilms (Kolari 2003).

Prior to the 1970s, however, the internal purification of process flows was scarce and these components were able to accumulate freely in the circulation water. Save-all systems equipped with disc filters or screens in their approaches served mainly to recover or remove gross contaminations and defloc the fibres, while the cleaners were designed to remove finer debris such as filler agglomerates, sand, shives and slivers (Smook 2002, Jokinen 2007) and were not suited for removing smaller contaminants, which were often denoted simply as dissolved and colloidal substances (DCS), although they also included wood extractives, salts and ink and sticky adhesives that were introduced into the systems as paper recycling became more common. Hence novel process solutions were needed to screen out the detrimental components of the circulation water, in spite of the fact that such white water cleaning measures can add complexity and expense to the operation of a paper mill (Hubbe 2007b).

Several applications for water purification are commercially available at present. One common practice is chemical treatment of white water that is targeted at specific detrimental components and their removal. Biocides and similar pesticides are used to control bacteria and other organic pollutants (Rossmore 1994). Passivation chemicals, enzymes and surface-active fillers are available to render sticky contaminants such as pitch components and stickies from recycled paper incapable of agglomerating (Sihvonen et al. 1998, Park et al. 2004, Guéra et al. 2005, Hubbe et al. 2006).

Similarly, various fixing agents are commonly used to increase the retention of contaminants on fibres and to remove them from the system via the paper (Meixner et al., 1998, Dechandt et al. 2003). Chemical water quality management applications are often problematic, however, as the chemical stability of the paper machine wet end can be compromised if new functional chemicals are introduced into the system. Substances enhancing process purity may cause adverse runnability effects or detract from the operation of the retention system, for instance, possibly resulting in fouling of the filters (Kyllönen et al. 2005) and the deposition of aluminium soaps (Ohtani & Shigemoto 1991). Also, bacteria have a tendency to become resistant to biocides, which requires active management measures and variation of the chemicals and their doses (Kolari 2003, Lahtinen et al. 2006, Kanto-Öqvist 2008).
Other means of removing detrimental components is to treat white water in an internal unit, commonly referred to as a “kidney” that would reduce the accumulation of substances in the system (Pauly 2001, Alexandersson 2003, Gabl et al. 2006, Hubbe 2007b). Such a design should consequently be regarded as an internal treatment process working in parallel with the paper production and not as an external treatment connected in series with production (Alexandersson 2003). The internal “kidney” could house several components, depending to a great extent on the actual type of production and the contaminants present. The different processes assessed for the internal kidney in the literature include at least evaporation, membrane filtration, sand filtration, dissolved air flotation, settling, ozonation, and chemical or biological treatment (Alexandersson 2003, Hubbe 2007b). The arrangement for kidney purification within the paper machine process is shown in Fig. 3.

Fig. 3. Generalized diagram showing how an inline treatment system utilizing some form of water purification “kidney” can be incorporated into a paper mill process. (Hubbe 2007b, © Martin Hubbe).

A few practical problems limited the wider use of these purification process configurations for a considerable time, and they are still viewed more as a part of high end product processes than as commonplace issues affecting any paper machine installation. This relates to the investment and operational expenses caused by the additional purification processes and also the concern as to how to
make use of the waste generated. Many such kidney installations have been completed, however, operating on principles such as ultrafiltration by membrane foils, biological and enzymatic water treatments, chemical coagulation of white water, and distillation with multiple-effect evaporators (Park et al. 2004, Hubbe 2007b).

Recent experimentation has been concerned with flotation arrangements for wet end circulation purification to rival other kidney technologies (Dionne et al. 2007, Ricard et al. 2008, De Grado et al. 2010). Although the results appear to be promising, there is a scarcity of information on the applicability of flotation to white water purification and the efficiency of component removal, especially with respect to the selectivity of contaminant separation and the degree of unwanted solid losses caused by water frothing. These issues have been investigated in Haapala et al. (2010a) and the Paper IV of this thesis, in conjunction with flotation residual gas content management.

2.5 Benefits of papermaking process water purification

The problems related to paper production efficiency, runnability and product quality connected with the various contaminants present in paper machine stock streams and white water are widely recognized in previous investigations (e.g. Sitholé & Allen 2002, Hubbe et al. 2006). Sticky materials can form deposits on the process equipment, clog the wires and pressing felts or stick to the drying cylinders, resulting in holes and dark spots in the paper and web breaks (Allen 1980, Kolari 2003). Coloured particles cause a deterioration in the optical quality of the paper, while particles and flocks of arbitrary size and shape can lead to web defects and breaks (Haapala 2005). Wood resin is also reported to have detrimental effects on paper friction (Back & Danielsson 1987), web strength and retention (Springer et al. 1985, Allen et al. 1999, Lee et al. 2006) and also the optical properties of the paper (Ricard & Dorris 2007, Hubbe et al. 2008, Ricard et al. 2008). All these issues ultimately detract from the profitability of the process and therefore continue to be of interest to papermakers.

Deposition problems have traditionally been controlled by means of dispersing agents and fixatives and by avoiding changes in the process conditions that might promote pitch agglomeration and deposition (Allen 2000). Pulp and water purification measures have mostly been introduced in the early phases of pulp treatment, and the paper machine loop has received less attention, although various versions of the “kidney” concept introduced in section 2.4 have been
applied to several processes. It is obvious, however, that even a moderate removal of accumulating material from the dispersed phase can substantially slow down the build-up of contaminants, reduce the equilibrium level of detrimental substances and improve runnability and product quality (Xu & Deng 2004, Hubbe et al. 2006, Paper III).

Benefits are likely to accrue in a mill-scale process through improved runnability, increased production time, better drainage and longer times between washes, and it is possible that there may be improvements in sheet quality through the absence of defects and elevated brightness (which results in a lower requirement for pulp bleaching) and reduced dosing of anti-foaming agents and fixing agents. The impacts and benefits obtained are likely to be greatest for the paper machines that suffer most from a detrimental contaminant load.
3 Experimental environments, materials and methods

The present experiments were mainly performed in the Fibre and Particle Engineering Laboratory at the University of Oulu. Some material characterisations, gas content and bubble motion analyses with high-speed CMOS cameras, elution analyses and bacterial cultivations from white water samples were conducted in co-operation with VTT Jyväskylä, the Laboratory of the Energy and Process Engineering at Tampere University of Technology, the Laboratory of Wood and Paper Chemistry at Åbo Akademi University and the Department of Food and Environmental Sciences at the University of Helsinki.

The experimental work was focused partly on the characterisation of bubble motion in paper mill white water, the assessment of channel flow deaeration efficiency and the most important related design factors, and partly on investigating the selective frothing of white water during the gas separation process.

This chapter introduces the materials and methods used in the experimental work. The experimental setups and measurement methods used in the gas separation studies included in Papers I and II are presented in section 3.1, while section 3.2 illustrates the environments and methodologies used in the white water flotation studies reported in Paper IV. The experimental work and analyses reported in Paper III were largely conducted at a paper mill site and are only briefly summarized in section 3.3. A survey of the materials and white waters used is given in section 3.4. More detailed descriptions of the experimental setups, the materials, their characterisation and the analyses carried out are reported in the original publications.

3.1 Deaeration of white water

Two experimental setups were used in this work to study the performance of bubble buoyancy-driven white water deaeration. The flow channel deaeration process and its performance were investigated in a pilot plant installation in which volumetric gas content measurements were performed using microwave analysers, while the more detailed measurements of the rise velocity and drag of microbubbles in white water were performed in a laboratory bubble column by means of the direct imaging (DI) and tracking of rising bubbles with a high-speed camera against a submerged laser backlight.
3.1.1 Development and efficiency of channel flow deaeration

The pilot scale experiments were conducted in the channel flow setup illustrated in Fig. 4, in which the deaeration phenomenon was studied with suspension batches of 8–10 m³ at a time, using discharge rates of 20–40 L/s into the test channel through an inlet pipe of diameter 110 mm to test the effects of residence time, air entrainment and mixing intensity on the gas content of the flow. The measured inflow pipeline pressures were 60, 100 and 150 kPa, respectively. The dimensions of the rectangular flow channel were altered according to required flow residence time, but most experiments employed a channel of length 4 metres with a 1° base slope in the direction of flow and a width of 1 metre with a flow surface height fixed at 0.5 metres. The hydraulic jump from the pipeline flow into the open channel flow was designed to mimic the gas mixing phenomenon typical of white water upon collection after drainage from the paper machine.

![Flow chart of the channel flow deaeration test setup](image)

Fig. 4. Flow chart of the channel flow deaeration test setup in the pilot process. The flow progression is clockwise in a closed loop from the temperature-controlled storage tank to the flow channel and back. The gas content of the suspension flow was measured with microwave analysers (QI) embedded in the pipelines or submerged in the channel flow. (Haapala et al. 2008, © Haapala et al.).
An elevated gas content was achieved in the white water feed to the channel by means of a membrane tube diffuser (ABS Nopon HKP 600) embedded in the pipeline (Fig. 5). The Reynolds number of the flow was determined as \( \text{Re} = \frac{UL}{\nu} \), where \( \nu \) is the kinematic fluid viscosity and \( U \) and \( L \) are the characteristic velocity scale and length scale (i.e. hydraulic radius) of the flow. The channel flow was markedly turbulent in all cases (Chanson 2004). The average channel flow velocity was defined as \( v = \frac{QA}{A} \), where \( Q \) is the fluid inflow rate and \( A \) is the cross-sectional area of the channel. Bubbles that were unable to surface within the residence time provided were drained through an outflow pipe and this gas fraction was taken as the residual gas content that defined the total degassing efficiency. The parameters of channel flow deaeration studied with this setup are summarized in Table 1.

![Fig. 5. Bubbly gas injection into the channel flow feed pipeline. (Stoor et al. 2005).](image)

<table>
<thead>
<tr>
<th>Materials</th>
<th>Measurements</th>
<th>Parameters tested</th>
<th>Paper</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tap water</td>
<td>Total gas content reduction in open channel flow</td>
<td>Flow discharge rate, Inflow gas content</td>
<td>Haapala et al. 2008</td>
</tr>
<tr>
<td>White water from a fine paper machine</td>
<td>Dynamic changes in gas content along the channel flow</td>
<td>Difference in deaeration performance between materials</td>
<td></td>
</tr>
<tr>
<td>Tap water</td>
<td>Total gas content reduction in open channel flow</td>
<td>Flow discharge rate, Flow residence time</td>
<td>I</td>
</tr>
<tr>
<td>White water from a fine paper and a virgin newsprint machine</td>
<td>Air feed into the flow channel (to promote froth formation)</td>
<td>Haapala et al. 2010a</td>
<td></td>
</tr>
<tr>
<td>White water from two RCF newsprint machines</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
3.1.2 Measurement of the bubbly gas content of a channel flow

The measurement method used to investigate entrained air was based on the propagation time of microwaves between the transmitter-receiver couple with a repeatability of ±0.01% and a sensitivity of 0.001%, as given in the manufacturer’s specifications. The gas content was measured in Paper I and Haapala et al. 2008 in the channel inflow and outflow (accept) pipelines, in addition to which spatial and temporal variations in local gas content were examined in Haapala et al. 2008 with a submerged modification of the same analyser. In these cases the measurements were made at different positions within the open channel flow in terms of length, width and height.

The gas content was measured at different locations (on the xyz axes) within the white water flow in the channel and the online results were averaged over 3 minutes of steady-state flow, as the variation in gas content was notably higher than the measurement accuracy of the microwave analyser. Furthermore, this method is not affected by the grade, solids consistency or optical properties of the pulp or fibre, but it is sensitive to changes in filler and gas content (Stoor 2006). Each measurement volume was 10 cm in height, and thus the total channel depth of 50 cm could be divided into five superimposed measurement layers, or zones, as depicted in Fig. 6, which also illustrates the changes in flow and gas separation in the channel as the flow progresses.

Fig. 6. Channel flow characteristics and measurement levels. Regions A to C describe the development of the flow and the deaeration phenomenon and zones 1 to 5 the levels at which measurements were taken. Similarly, 5 measurement points were located evenly across the width of the channel (z axis). The proportions of regions A-C are indicative schematically and are dependent in practice on the discharge rate and channel dimensioning. (Haapala et al. 2008, © Haapala et al.).
3.1.3 Analysis of microbubble dynamics

The microbubble motion experiments were carried out in a closed, pressurised laboratory bubble column of length 1200 mm and diameter 167 mm (Fig. 7) in which 20 litres of suspension was subjected to a steady internal pressure of 300 kPa maintained by feeding pressurised air at 25°C in through a sintered porous medium (Schott Duran #2 glass filter plate) at 400 kPa, allowing a continuous flow of finely dispersed bubbles through the column, accelerating the gas dissolution onto the studied suspension. The amount of dissolved oxygen in the water increased until the saturation level of the suspension was reached, as monitored using a dissolved oxygen analyser (Hach Orbisphere 3600).

Fig. 7. Experimental setup for the microbubble motion experiments, consisting of a pressurised bubble column, a high-speed CMOS camera and a submerged laser backlight. Gas was dissolved in a process suspension under elevated pressure and microbubbles were generated by a sudden drop in pressure. A synchronised pulsed laser and high-speed camera were used to capture images of the rising microbubbles from which their size, velocity and drag could be determined. (Paper II, © Elsevier).

After feeding air in to saturate the suspension, a pressure drop was created by opening a solenoid valve at the top of the column. Images of the microbubbles generated in this way were gathered through a 300 mm high mid-section of transparent polycarbonate piping over a period of 30 seconds after the first microbubble appeared. Mill water samples were tested at 40°C to obtain similar
physical suspension characteristics to those that occur in a real process environment, while the tests performed with tap water and model suspensions took place at 20°C.

A high-speed digital imaging setup was used to visualise the rising of the microbubbles at a point approximately 5 mm from the bubble column wall. Imaging was limited to regions near the wall, as dispersed solid particles blocked the view deeper in the suspension. The flow was illuminated with a submerged light diffuser connected to a pulsed diode laser (Cavilux Smart, 400 W, 690 nm) by an optical fibre. A control unit synchronised the laser with the high-speed CMOS camera (PCO 1200hs), while measurements were user-controlled via a laptop computer. The high-speed camera was placed outside the column at a point opposite the submerged light diffuser to provide shadow images of the microbubbles in the flow between the light diffuser and the column wall. To eliminate image distortions due to the curved column wall, an external cubical basin filled with water was placed around the bubble column. Image scaling with a measuring rod provided a scale of 18.6 µm per image pixel.

The high-speed image sequences were analysed automatically using image analysis algorithms. After recognition of the microbubbles, three consecutive image frames were analysed to link the images that belonged to the same bubble. A constant rise velocity and size for each bubble was assumed, allowing a maximum of 20% variation in the pseudo-distance. The microbubble size distributions were then discretised into bubble size classes with an equal width of 0.05 mm and size range from 0.1 to 1 mm. The microbubble recognition technique, the tracking algorithm and the dynamic analysis of bubble motion used here are presented in more detail in Paper II.

The hindered efficiency of bubble rise in multiphase process water was related to a bubble drag coefficient ($C_D$), which is a dimensionless quantity used in fluid dynamics to represent quantitatively the resistance of a moving object in a fluid. In our case, the drag of a bubble states the magnitude of the sum of forces opposing the upward motion of each bubble, including the viscous forces. The bubble drag coefficient was estimated according to a simplified momentum equation, assuming a steady flow in which only the drag and buoyancy forces affect the bubble motion, as shown in Eq. 1.

$$
\sum \vec{F} = \frac{1}{2} C_D \rho_L \left| \vec{U}_b - \vec{U}_i \right| \left( \vec{U}_b - \vec{U}_i \right) \cdot \left( A_b \left( \rho_b - \rho_L \right) \cdot V_b \cdot \vec{g} \right), \quad (1)
$$
where $A_B$, $V_B$ and $U_B$ are the surface area, volume and rise velocity of the bubbles, $\rho_L$ is the fluid density and $U_L$ is the fluid velocity obtained as the instantaneous mean fluid velocity in the measurement plane. Interactions between microbubbles were neglected in the analysis, while interactions between the dispersed particles in the suspension and the microbubbles were included in the bubble drag coefficient, which was obtained according to Eq. 2.

$$C_D = -\frac{(\rho_b - \rho_L)}{\rho_L} \frac{4}{3} \frac{d_B \bar{g}}{(U_B - U_L)^2} \approx \frac{4}{3} \frac{d_B \bar{g}}{(U_B - U_L)^2},$$

where $d_B$ is the bubble diameter. The microbubble drag in white water was compared with the extreme cases of bubble surface contamination presented in literature. The drag coefficient for a clean microbubble that has a fully movable surface was given as an empirical correlation as proposed by Mei et al. (1994), providing a theoretical minimum for $C_D$ for each given bubble size. Similarly, the upper limit of the drag in a two-phase system was estimated in terms of microbubbles with a completely rigid surface, according to the correlation presented by Putnam (1961).

As the drag measurements were made in a confined vessel and relatively close to the column wall, it was necessary to quantify the effect that the wall has on the bubble drag. The bubble rise velocity in the column relative to the velocity in an infinite volume was defined according to Clift et al. (1978), whereupon the wall effect in our measurement setup, as calculated for a liquid having the properties of white water, was found to be an increase in bubble drag of about 5% at 5 mm from the wall and 25% at 1 mm. Since it has been shown by Chhabra (2006) that the wall effect is markedly less severe in non-Newtonian power-law fluids than in Newtonian fluids, the wall effect was not taken into account in the microbubble motion analysis.

### 3.2 Purification of white water by flotation

Two experimental setups were used to study the performance of white water purification by flotation. The ability of white water to form froth in the presence of flotation aid chemicals, the efficiency of contaminant removal in relation to losses of beneficial solid components and the selectivity of contaminant separation were assessed in a laboratory flotation setup. A novel process application that combines white water deaeration in channel flow with flotation...
purification of the circulation water was investigated in a two-stage pilot arrangement. The results obtained from these two flotation stages were then used to calculate the total separation efficiency of a simulated two-stage white water flotation process.

3.2.1 Laboratory flotation studies

White water flotation was studied in a Voith Delta25 batch laboratory flotation cell. The intense mixing of air and water in the cell were considered comparable to the early stages of channel flow deaeration where the flow discharge causes considerable mixing of air into the flow. The white water was pre-heated and held at 45°C for 15 minutes before weighing a sample batch for the flotation cell. No additional chemicals were used. Batches were floated with residence times from 30 seconds to 5 min, while the air feed was set at 7.4 L/s (mode 10). The resulting froth was continuously removed, and the liquid phase was studied for detrimental contaminants (ink, stickies and wood extractives), while the liquid head was maintained constant during frothing. Each batch volume was weighed together with the froth that had been removed, and samples were taken before and after flotation for analysis.

Each sample was studied for dry matter and ash content, whereas analysis of the amounts of stickies and extractives was limited to the feed, certain points after flotation and a few froth samples. The analysis of flotation removal efficiency was based on the removal of white water solids in relation to the analyses of detrimental substance contents. The yield of flotation solids was related to the flow and froth reject in terms of mass reject rate ($RR_m$), and the contaminant separation efficiency $E_c$ was analysed by means of Eq. 3 (Hautala et al. 1999).

$$E_c = \frac{m_R \cdot x_A}{m_f \cdot x_f} = 1 - (1 - RR_m) \cdot \frac{x_A}{x_f},$$

where $m_R$ and $m_f$ are the masses of the reject (froth) and feed (white water), except in continuous flotation processes, where the mass flow rate notation $\dot{m}$ is used instead of mass. $RR_m$ is the mass reject rate, $dmc_R$ and $dmc_f$ are the dry matter content of the samples and $x_R$, $x_f$ and $x_A$ are the detrimental substance contents of the reject, feed and accept fractions.

The selectivity of component removal in flotation, i.e. the efficiency of the process in removing specific components, was estimated in a similar manner to that adopted by Jokinen (2007) and Körkkö et al. (2008), according to the Q-
index ($Q_N$) originally introduced by Nelson (1981), as given in Eq. 4. Selectivity is not dependent on the process reject rate, and it considers the quality of both the accept and reject fractions. Traditionally this notation has been used when analysing screening and cleaning operations, but it is of comparable relevance to flotation as well. The selectivity index $Q_N$ has values from zero to one, where zero indicates a split flow, i.e. no selectivity, and positive values indicate the level of component enrichment in the froth. At unity, $Q_N$ corresponds to perfect separation of only the desired component from the bulk of the suspension flow, which of course remains a theoretical concept in practice

$$E_r = \frac{RR_m}{1 - Q_N + Q_N \cdot RR_m}, \text{ with } Q_N = 1 - \frac{x_A}{x_R}.$$  \hspace{1cm} (4)

### 3.2.2 Pilot-scale flotation trials

The flotation trials took place with a two-stage separation system of bubbly gas and white water contaminants. The first separation stage took place in the same flow channel installation as the aforementioned deaeration experiments, the flow arrangement being modified by housing four air feed membrane tube diffusers (Ecologix Technologies Hyotube 7–500F) to the base of the beginning of flow channel and providing it with an overflow, which allowed separation of the froth layer and the gas-rich channel flow surface layer from the bulk of the white water. The channel dimensions were width 1 m and length 4 m, and the surface level was fixed at 0.5 m, giving the flow a residence time of approximately 40 seconds. The white water temperature was kept at 45°C during the trials. The modified system is illustrated in Fig. 8, where the channel flow initially goes through an intense mixing phase and then gradually calms to a quasi-laminar flow, as depicted in Fig. 6.
The channel flow loop was run as a continuous single-stage flotation where the white water was tested in batches of approximately 8 m³. The circulation was operated as a closed loop at first to achieve a steady-state process, and then approximately 800 litres of overflow with the generated froth, i.e. the reject, was collected and treated separately in a secondary flotation cell. Each white water sample was tested both with and without an external air feed.

At first froth was formed only by the gas mixing due to the discharge of white water into the channel flow, but in the “flotation mode” the air feed through the membrane tubes (780 L/min) at the beginning of the channel flow was used to enhance froth formation. Air was fed into the channel flow in the form of macrobubbles ranging from 1 to 3 mm in diameter, as in the manufacturer’s specifications. Samples taken before and after flotation were analysed for solids, ink, stickies and extractives.

The overflow from the first flotation stage was collected in a container from which it was later fed into the 2nd flotation stage independently of the operations in the first loop. Here a 65 L continuous flotation cell was operated at 45°C with an inflow rate of 12 L/min and an airflow of 20 L/min. These parameters were verified as applicable in a preparatory study. The air-water ratio was hence at the moderate level of 165% and the residence time of the white water in the flotation cell was slightly over 5 minutes. The modified system is illustrated in Fig. 8.
Fig. 9. Flow chart of the pilot-scale channel flow deaeration and froth flotation test setup. The arrangement is analogous to the deaeration setup presented in Fig. 4, with the addition of a bubbly air feed into the channel flow base through membrane foils and the installation of an overflow for circulation and collection of the reject (froth and air-rich surface flow fraction). (Haapala et al. 2010a, © Haapala et al.).

The flotation reject was continuously returned to the feed container and samples were collected from the secondary flotation only after operation of the cell was considered to have reached a steady state. These samples were analysed for solids, ink, stickies and extractives in the same way as the first stage samples.

The removal efficiency of the two-stage white water flotation scheme was determined in a model process combining channel flow flotation with secondary flotation in a forward-connected cascade, as shown in Fig. 10. This simplified flow chart depicts one possible example of the two-stage integrated flotation process and enables evaluation of its total efficiency in terms of mass balances based on the data obtained from the individual stages. The total removal efficiencies of the process were calculated from the channel feed (F) and the total process reject (R_{OUT}) by means of Eq. 3.
3.3 Paper machine runnability and web defects

The role of pulp and white water contaminants with respect to the process efficiency of a paper machine was tested in a mill case study. In order to identify the causes behind defect formation on a paper web, a series of chemical and bacterial analyses were performed on the process suspension and end product. Changes in production, defect formation and web breakage rates were observed during the trial via a process monitoring and Ulma Nti web monitoring system (ABB, Finland). The effect of chemical treatment on pitch aggregates was monitored by staining and microscopy for evaluation of the pitch content, and the biocide trials were similarly evaluated based on cultivations and PCR analyses of process samples. These trials are reported in detail in Paper III and in Haapala (2005).

Defect formation and web breakages were analysed on a single 1500 m/min newsprint machine of width 8.5 m with fairly closed water loops. The process used mainly dithionite-bleached virgin spruce TMP and PGW pulps with GCC filler as the primary raw materials. The retention system was based on a bentonite and cationic polymer. The products ranged from standard newsprints to special grades of directories and speciality newspapers of 36–49 g/m² grammage and 50–65% ISO brightness range.

The web monitoring system was used to obtain statistical information on the size, number, defined class and web position of holes and other defects. This information was then categorised in terms of wet holes, slime holes or
condensation droplet holes according to the TAPPI guidelines (Smith 2007) and observed processes, or in terms of sheet faults as described by Roisum (1990).

### 3.4 White water and other materials

Several types of white water were studied in sub-projects connected with this work. Due to the dynamic nature of papermaking processes, the samples obtained from mill sites at different times were never entirely the same. The deaeration studies made use of a very wide range of mill water in order to be able to generalise from bubble motion results obtained with different media, while the white water purification studies were mostly performed on white water containing contaminants from mechanical and recycled pulps. A summary of the types of white water used in different parts of this thesis is given in Table 2.

#### Table 2. White water specimens tested and their origins.

<table>
<thead>
<tr>
<th>White water</th>
<th>Mill characteristics and white water contaminants</th>
<th>Parameters Tested</th>
<th>Paper</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fine paper machine</td>
<td>WFC paper machine, kraft eucalyptus and hardwood fines, PCC filler</td>
<td>Composition, Gas separation, Microbubble motion</td>
<td>I, II, Haapala et al. 2008</td>
</tr>
<tr>
<td>Fine paper machine</td>
<td>MWC paper machine, kraft birch and hardwood fines, PCC filler</td>
<td>Composition, Microbubble motion</td>
<td>II</td>
</tr>
<tr>
<td>Fine paper machine</td>
<td>LWC paper machine, kraft birch and hardwood fines, PCC filler</td>
<td>Composition, Microbubble motion</td>
<td>II</td>
</tr>
<tr>
<td>SC paper machine</td>
<td>Spruce GW, kaolin filler</td>
<td>Composition, Microbubble motion</td>
<td>II</td>
</tr>
<tr>
<td>Virgin newsprint machines</td>
<td>Spruce PGW and TMP fines, GCC fillers</td>
<td>Composition, Gas separation, Microbubble motion, Process contaminant content, White water frothing</td>
<td>I, II, III, IV</td>
</tr>
<tr>
<td>White water from RCF newsprint machines&lt;sup&gt;1,2&lt;/sup&gt;</td>
<td>100% DIP fines&lt;sup&gt;1&lt;/sup&gt; 35% TMP and 65% DIP fines&lt;sup&gt;2&lt;/sup&gt;</td>
<td>Composition, Gas separation, Microbubble motion, Process contaminant content, White water frothing</td>
<td>II, I V, Haapala et al. 2010a</td>
</tr>
<tr>
<td>White water from OCC process</td>
<td>100% DIP fines</td>
<td>Composition, White water frothing</td>
<td>IV</td>
</tr>
</tbody>
</table>

<sup>1,2</sup> White water obtained from two separate RCF processes.
Relatively pure tap water or other model suspensions were also used as references in the deaeration studies. Simple model suspensions were used to analyse the effects of single variables, since in the case of mill water all the properties differed, making the analysis difficult. The model suspensions used are summarised in Table 3.

Table 3. Model suspensions tested.

<table>
<thead>
<tr>
<th>Model suspensions</th>
<th>Chemical content</th>
<th>Usage or modified suspension property</th>
<th>Paper</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tap water</td>
<td>Low concentration of salts, no solid components</td>
<td>Deaeration reference</td>
<td>I, II</td>
</tr>
<tr>
<td>Carboxymethyl cellulose (CMC)</td>
<td>CMC w/o refined kraft fibres</td>
<td>Elevated viscosity dispersed particle content</td>
<td>II</td>
</tr>
<tr>
<td>n-butanol</td>
<td>n-butanol w/o refined kraft fibres</td>
<td>Lowered surface tension dispersed particle content</td>
<td>II</td>
</tr>
</tbody>
</table>

Each white water and model suspension sample was analysed for its characteristic physico-chemical properties using standard methods, analyses of white water contaminants also being made in connection with the purification studies (Paper IV and Haapala et al. 2010a). Furthermore, specific determinations of paper and process deposits were made as part of the assessment of paper machine runnability and defect formation (Paper III). These analyses are briefly presented in the following sections and described in more detail in the original papers.

3.4.1 Analyses of white water properties

Measurements of pH (SFS 3021) and conductivity (SFS 27888) were made with a Denver Instrument Model 50 device, and the dry matter content (dmc, SFS-EN 20638) of the suspension mass and ash content (ISO 1762) of the dried suspension mass were obtained gravimetrically using a Precisan prepASH 129. Suspended solids were analysed in relation to the suspension mass by filtration according to SFS-EN 872. Surface tension was measured by du Noüy’s ring method with a Krüss K8600 meter and viscosity either with a Haake 501 viscometer and NV spindle at 3200 rpm, or with a capillary viscometer according to SCAN-CM 15:99. Water hardness, i.e. the concentration of calcium and magnesium ions, was measured using a Perkin Elmer AAnalyst 600 atomic absorption spectrometer according to SFS 3044 and SFS 3018. The particle sizes
of white water solids were determined using a multi-wavelength particle size analyser (Beckman Coulter LS 13 320).

### 3.4.2 Analyses of white water contaminants

Wood extractives and stickies in the water samples were analysed at Åbo Akademi University by extraction with methyl tert-butyl ether (MTBE) followed by high performance liquid chromatography (HPLC), a method modified from MacNeil et al. (2006) and Ōrså & Holmbom (1994). The water samples were freeze-dried before extraction by reflux with 20 mL tetrahydrofuran (THF) for 1 hour. They were then acidified to less than pH 4 by adding 0.05 M H$_2$SO$_4$, after which they were extracted three times sequentially with 4 mL of MTBE. They were vigorously shaken for 1 minute before centrifugation to separate the solvent and water phases. After removing the solvent phase and combining it with the other extracts, the solvent was evaporated under nitrogen gas until dry and the sample re-diluted in 1 mL of THF. A similar method was previously used by Sarja (2007). The variance in the measurements reported by Johansson et al. (2003) for similar extractions gives an estimate of 4.6% for the repeatability of the method.

The samples dissolved in THF were subsequently injected into an HPLC system consisting of a size-exclusion column (Jordi 550A) and an evaporating solvent light scattering (ELS) detector (Sedex 80) with a nebulizer temperature of 40°C. The eluant was THF at 1.0 mL/min. The system was calibrated externally against a solution of C21:0 in THF. The total material extracted was obtained by quantification of the HPLC-SEC chromatograms for the 5 main groups individually, presented as mg/g in relation to white water solids. A sample chromatogram with the 5 groups is shown in Fig. 11. Peak separation was obtained using the peak fitting software available in Origin 8.0.
The ink content of the water was measured from low grammage sheets with a Lorentzen & Wettre Elrepho 070 spectrophotometer according to the method described in detail by Haapala et al. (2009). The prepared sheets satisfied the opacity limitation for scattering coefficient measurements (below 97%). Pitch particles in the pulp and water samples were quantified microscopically from diluted samples stained with Sudan IV, and bacterial DNA content was measured by quantitative PCR (polymerase chain reaction) as described by Ekman et al. (2007) to identify the microbial genera capable of forming biofilms.
4 Passive white water deaeration in channel flow

This chapter addresses hypothesis 1 and presents the results appertaining to open channel flow deaeration and microbubble dynamics. The composition and flow behaviour of white water will also be discussed, illustrating the importance of dispersed phase particles, liquid phase physico-chemical properties and general flow dynamics as related to buoyancy-driven gas removal. The deaeration studies presented here focus on the removal of detrimental bubbly gases as, according to the previous studies of Stoor (2006) and Helle (2008), for example, the dissolved gases present in suspensions have proved to have negligible effects on the papermaking process. However, as stated in previous studies (Matula & Kukkamäki 1998, Stoor 2006, Helle 2007), the dissolved gases can precipitate into bubbly gases if the process conditions change and disturb the process as bubbles.

4.1 White water properties affecting deaeration

The separation of gas bubbles from the white water of a typical paper machine is much more difficult than the deaeration of pure water (Papers I-II). One reason for this is that the air bubbles in contaminated water are often stabilised by surface-active agents (Okazaki 1962, Heindel 2002, Takagi et al. 2008, 2009) which keep the bubbles small and hinder their coalescence.

The motion of bubbles in stagnant liquids is mainly governed by viscosity, surface tension and inertial effects, but the constantly changing patterns of flow in practical papermaking processes and the presence of solid components in their multiphase suspensions have substantial effect on this motion. In general, once the channel flow progresses past the turbulent initial mixing stage the larger bubbles will rise and evacuate the system faster with their buoyancy than smaller ones in the same medium, unless their motion is hindered by collisions or the attachment of solid particles (Cui & Grace 2007, Hassan et al. 2008). Large bubbles also tend to lose their spherical shape and their motion begins to oscillate, becoming impossible to evaluate accurately in terms of any of the principal theories of hydrodynamics. The critical bubble size at which this occurs depends on the properties of the liquid medium, such as its surface tension.
Microbubble formation in white water was studied in Paper II. The size distribution of microbubbles in relatively pure tap water and several samples of white water is presented in Fig. 12, where also the effect of lowering the surface tension of the process water can be seen. The bubbles in the white waters are clearly smaller than those in the tap water, while the differences in bubble size distribution between the white water samples are small despite the apparent differences in their composition and properties.

![Fig. 12. Size distributions of microbubbles formed by a pressure drop in tap water and several white water samples. (Paper II, © Elsevier).](image)

No coalescence between microbubbles was detected in the white water samples, which means that bubbles in process water tend to remain small in size, which effectively means that they are also slow to rise due to their limited buoyancy. This result is in line with that of Tang and Heindel (2005), who also report that the surface-active agents present in pulp suspensions usually reduce the surface tension of the liquid phase and produce smaller, more stable bubbles. This stabilizing effect is commonly caused by the resin and fatty acids in wood, sizing chemicals, surfactants used in deinking and various deposit control chemicals, for instance. The lowered surface tension and elevated viscosity of white water relative to pure water was also noted in Papers I-II. It is difficult to generalise from white water properties, however, on account of the vast numbers of raw material and process chemical configurations used in mills. Hence bubble motion remains to be determined for each suspension separately.

Furthermore, the presence of dissolved and dispersed phase substances generally elevates the viscosity of the suspensions and lowers their surface tension.
tension, but it also increases the rate of bubble-particle collisions and consecutive attachments, which contribute to reducing the rise velocity and increasing the drag, as observed in Paper II. This phenomenon is identical to the bubble-particle interactions observed in the flotation treatment of recycled pulps and effluent waters, and also in water purification outside the paper industry (Clift et al. 1978, Nguyen 1998).

Hydrophobic interactions are always attractive, and thus they can increase adhesion between a bubble and a hydrophobic particle, effectively leading to contamination and the attachment of solid particles to bubble surfaces. Analysis of the high-speed image sequences shown in Fig. 13 reveals that the larger particles and fibres often attach to microbubbles and reduce their rise velocity, as the bubbles now have to “drag” these particles as they rise in the suspension. This is seen to have the most severe effect on the drag and holdup of the smallest bubbles (Liger-Belair et al. 2000, Tang & Heindel 2005).

Fig. 13. Images of bubbles used for the analysis of a selection of white waters. The upper row shows a single image frame and the row below shows three consecutive images in which the same bubbles are identified and followed in the suspensions. (Paper II, © Elsevier).

The results indicate that the buoyancy of some microbubbles is not sufficient to detach them from flocculated fines and fibres so that they tend to remain trapped within the suspension. Hence passive channel flow deaeration remains of limited efficiency and the rate of removal of small microbubbles defines the gas separation efficiency that can be attained. The tendency of contaminants to adhere to bubbles can also be beneficial and can be of use in flotation applications of to
remove inks, adhesives and wood extractives from recycled pulps and circulation water, as discussed further in the following section.

4.2 Bubble rise velocity and drag in process waters

There has been much research into bubble rise in relation to bubble columns, waste water treatment, flotation and other industrial applications, but few research efforts have been focused on water deaeration. Even so, buoyancy driven passive deaeration operates according to the same basis, being highly dependent on the terminal velocity of the bubbles in white water. The lack of research in this field may be related to the predominant use of deaeration tanks in which the bubble dynamics play no significant role. The efficiency of passive gas separation methods, however, is heavily dependent on buoyant bubble rise and process water properties that may hinder bubble motion.

There are several theoretical and experimental methods for determining the velocity of rising bubbles, and many of these theories and phenomena have been well reviewed by Kulkarni and Joshi (2005) and Chhabra (2007), while various applications to papermaking have been presented by Stoor (2006). Experimental correlations that are applicable in a multi-phase environment are scarce, however, and many of them require specific flow conditions and suspension parameters to be applicable. The complexity of industrial flows relative to the typically quoted cases of stationary or laminar flow also makes the theoretical estimation of bubble motion a troublesome task.

Prediction of the terminal rise velocity of bubbles in suspensions under turbulent flow conditions, as in the case of circulation water deaeration in channel flow, requires knowledge of the drag force imposed on the rising bubbles. The most common general notation for motion in the case of gas separation was devised by Stokes (1851), who proposed that the constant terminal velocity of a bubble can be obtained from Stokes’ law of drag force for spherical particles, \( F_D = 6\pi \mu r \) as:

\[
\tag{5}
\begin{align*}
  u_b = \frac{2gr^2(\rho_l - \rho_g)}{9\mu},
\end{align*}
\]

where \( r \) is the bubble radius, \( \rho_l \) is the liquid phase density, \( \rho_g \) is the gas density and \( \mu \) is the dynamic viscosity of the medium. Although this is a common correlation, its applicability is fairly limited. As stated, gas bubbles are not always perfectly spherical in form, as larger bubbles in particular tend to undergo...
deformation under stress from the flow. Stokes’ law has also been shown to apply only under conditions of laminar flow with a Reynolds’s number less than 0.5 (Vauck & Müller 1992). In addition, relatively recent experimental work has demonstrated that the rising speeds of bubbles larger than 100 μm deviate from those calculated by Stokes’ formula (Clift et al. 1978). As the flows in industrial processes are always highly turbulent and bubbles are present in varying sizes from minuscule to a centimetre scale, it can be stated that models describing ideal cases based on Newtonian flow mechanics are not applicable to industrial multiphase process flows.

Numerous other empirical relationships for the drag coefficient of bubble motion have been reported in the literature since Stokes’ day, commonly relating $C_D$ to the Reynolds number ($Re_B$) for bubbles. These include a few drag models for bubbles in fibre suspensions (Brecht & Kirchner 1956, Reese et al. 2006). Models for cases of contaminated liquids or low consistency suspensions regularly give higher drag values than that proposed by Stokes, and the experimental values obtained for small bubble drag in white waters were still substantially higher than those predicted by drag models.

It was hence apparent that experiments performed specifically on paper mill white water were needed for an accurate analysis of deaeration efficiency. The main focus in the present work was on clarifying the dynamics of microbubbles in white water and determining their impact on deaeration efficiency.

The rise velocity and drag of microbubbles as measured in a bubble column for a variety of white water samples are given in Fig. 14. There are obvious differences in bubble motion between samples of white water. As noted in Paper II, water containing mechanical pulp fines and probably a much higher enriched wood extractives content (i.e. dissolved or colloidal wood pitch particles) would be more contaminated and the movement of microbubbles more restricted than in kraft pulp water.
Fig. 14. Left, drag coefficients of bubbles in white water (WW#) relative to the drag of a rigid sphere (Putnam 1961), and right, mean bubble rise velocities measured for white water. Reasonably clean tap water was used as measurement reference. White waters 1, 2, 3 and 5 contained primarily mechanical pulp fines, while the others had mainly chemical kraft pulp fines. (Paper II, © Elsevier).

The correlation for microbubble drag was constructed to incorporate the difference in bubble motion noted between white water containing mechanical pulp fines ($C_{D_1}$) and white water with only kraft pulp fines ($C_{D_2}$), as a notable difference is also likely to occur in deaeration applications. The empirical correlations obtained for both white water groups are presented in Eqs. 6 and 7, and the experimental correlation is illustrated graphically in Fig. 15.

$$C_{D_1} = \frac{120}{Re_B} + 1.6,$$

$$C_{D_2} = \frac{60}{Re_B} + 0.9.$$
As seen, the microbubble drag coefficients measured in the white water of paper machines deviate significantly from the drag models for contaminated and clean bubbles (Fig. 14). The power-law model fits well with the experimental data, and the overlap between the standard deviations relates to the mixed use of mechanical and kraft pulps in some paper machines (Fig. 15). The generalised correlations given in Eqs. 6 and 7 serve to illustrate that microbubble drag in process water deviates significantly from the drag curves for clean bubbles or rigid spheres, a fact which should be taken into account in process design and development concerned with gas separation.

4.3 White water deaeration efficiency in open channel flow

4.3.1 Characteristics of open channel flow

Open channel flow is characterized best as a flow of fluid driven by gravitation in a conduit which always has two sides, a bottom and a free surface. Flows of this kind are dominated by the effects of gravity, propelled by the weight of the water
flowing down a slope. By comparison, the more common pipeline flows are driven by the pressure gradient along the pipeline (Chanson 2004). The physical laws of hydrodynamics in open channels are essentially the same as those in closed pipes, but calculations of the boundary shear stresses are complicated due to the existence of the free upper surface and a wide variety of possible cross-sectional shapes (Chanson 2004, Chaudhry 2008).

The flow in a typical slightly inclined channel in which bubbles are to be removed can be characterised in many ways, including steady, turbulent, varied and non-uniform (Chaudhry 2008). The intensity of turbulence, flow residence time and amount of air entrainment in the white water can be controlled by channel dimensioning and design. This requires in practice numerical solution of the Navier-Stokes equations for the conservation of energy, mass and momentum with CFD tools. CFD models and the theoretical details needed for analytical solutions to the non-linear partial differential equations approximating the flow of non-Newtonian white waters are nevertheless left outside the scope of this experimental work.

### 4.3.2 Gas separation in open channel flow

The surge of white water into the channel causes continuous large and small-scale variation in flow, seen as eddies and fluctuating flow patterns when assessed visually and with a PUD anemometer as used by VTT. The flow was also noted to develop from highly turbulent at the beginning of the channel to more tranquil towards the end (Haapala et al. 2008). Although the surface level can be kept constant with an overflow, small variations continually occur due to waves and non-uniformities in the flow.

In the pilot-scale experiments the bubbles that were unable to surface within the residence time provided either became separated out by the surface water fraction via the overflow, or drained through an outflow slit into the accept pipeline. This gas fraction is taken to represent the residual gas content, thus defining the total degassing efficiency of channel flow deaeration as discussed in Paper I and Haapala et al. (2008, 2010a). This process is visualised in Fig. 16, where the results of a CFD model constructed in co-operation with Lappeenranta University of Technology depict the separation of entrained air bubbles of diameter 200 µm along the length of a channel flow.
The channel geometry in the model is the same as was used in the experiments, but the simulation ignores the free motion of the flow surface, reducing it to a static boundary through which transfer of matter takes place. This simplification detracts from the accuracy of the model, but it serves to illustrate the phenomenon of gradual degassing of a channel flow from the base upwards as the flow progresses.

Fig. 16. Progression of channel flow deaeration and the efficiency of evacuation of 200 µm bubbles from a slightly viscous model suspension. The flow simulation performed with Ansys CFX assumed a 2% gas content at the channel flow feed.

The magnitude of the difference between the theoretical and measured values for the bubble drag (Fig. 14) testifies to the lack of any simple theoretical considerations to describe the phenomena occurring in complex suspensions and flow structures. The flow model illustrated in Fig. 16, for example, ignores many interactions that contribute to the deaeration process, including bubble-bubble and bubble-particle interactions, gas mixing at the flow discharge and surface motion in the suspension, including waves and splashing, which can also entrain gas into the flow. Also, exact comparison of measured data with theoretical or simulated bubble removal is problematic without any knowledge of bubble size distribution along the progressing flow. Thus it was considered more practicable in the pilot-scale experiments to observe the change in the total volumetric bubbly gas content than to look for the probabilities of certain bubble sizes being evacuated from the channel flow.

4.3.3 Residual gas content in channel flow deaeration

The gas content of white water in channel flow is closely related to the intensity of the turbulence of that water, which varies according to the feed rate and the resulting air entrainment, as explained by Chaudhry (2008). As shown in Fig. 17,
the discharge rate and turbulence at the beginning of the channel flow has a significant effect on total gas entrainment and removal efficiency. The gas content at the flow surface, as given on the left in Fig. 17, remained consistently higher than that at the bottom, as seen on the right. Hence no substantial gas circulation was detected in the channel flow outside of the mixing zone. It is feasible to assume that a layer of white water that contains more dispersed bubbles will be lighter than a layer that contains fewer or no bubbles, and hence this gravitational difference would tend to suppress the mixing of the layers in a channel flow.

![Graph showing progression of entrained air removal from white water in channel flow.](image)

Fig. 17. Progression of entrained air removal from white water in channel flow. On the left, gas content measured at the flow surface, and on the right, entrained gas content at the bottom of the channel as it drains to the accept system. The measured inflow gas content for each case is given in parentheses. The change indicated with dotted lines depicts large variance in measured gas content due to turbulence intensity. (Modified from Haapala et al. 2008, © Haapala et al.).

The accept flow of white water after deaeration in a 4 m channel flow still contained some entrained gas, whereas the tap water quickly became fully deaerated. The slowest flow, with a discharge of 20 L/s, was deaerated to the level of 0.2% regardless of the inflow gas content, but more rapid flows with discharge rates of 30 L/s and 40 L/s only reached this level when their inflow gas content was practically zero. Given a 2% inflow concentration, the gas content in the accept was 0.35% and 0.46% at the two discharge rates, respectively. The turbulent mixing zone at the beginning of the channel flow intensified with increased flow rate and a higher gas content was measured in the flow due to air entrainment. The highest value for the 40 L/s flow was 8%, at a large eddy that formed 1 m downstream of the feed point.

The result indicates that the entrained air content at the end of the channel flow is closely related to the intensity of the early channel flow and the amount of gas present in the inflow stream. Both factors can be taken into account by
engineering the transition from the wire section drainage chute to the channel in such a way that the turbulent mixing stage of early channel flow is minimised.

It was also noted in Paper I and Haapala et al. (2008, 2010a) that white waters differ in their properties and in their ability to hold bubbly gases. The tap water used for reference was quickly and completely deaerated, while the process water always retained small quantities of entrained gas. The easiest white water to deaerate was fine paper mill water with a low hydrophobic contaminant content, fairly low solids consistency and only slightly elevated viscosity, the obtained residual gas content in this case being only around 0.2%. White water from a newsprint machine, containing mechanical pulp fines and therefore having notably higher solids content and viscosity reached levels of 0.2–0.3%, and thus was slightly harder to deaerate. This result is in line with the image analysis results for bubble drag and rise velocities. White water with both mechanical pulp fines and a substantial amount of fines and contaminants from deinked pulp similarly retained around 0.3% of its gas, while white water with a high solids content and only deinked pulp fines could be deaerated only down to 0.4%, representing the highest residual gas content measured with a standard pilot channel setup at a process temperature of 45 °C.

4.3.4 Sedimentation of solids and formation of froth in channel flow

Particle movement in open channel flow is closely related to flow behaviour and residence time. Turbulence and mixing hinder solid sediment formation as they keep the particles in a constant state of random motion. It can be generalised that solids with a large mass and high density area are most prone to settle on the bed of the flow channel, and in the case of white water, this concerns mostly fines and mineral fillers that are flocculated by the chemicals present in the wet end processes.

The surface properties of the channel floor and the interaction between particles determine how easy it is for a particle to attach to the channel bottom once it reaches it. In practice, fines and fillers in white water do not adhere to clean, polished surfaces, but if the deposits that form on these surfaces are not continuously removed, the formation of adsorbed layers is difficult to avoid (Bott 2006, Kallio 2007). In a recent study by González (2009), some sedimentation of white water solids was noted, becoming more substantial towards the end of the channel flow. The loose sediment layer in the white water was nevertheless seen to have high relaxation and low packing density when observed by analytical
centrifugation. This indicates that the sediment layer is very loosely bound and typically has a low consistency, being thus easily re-entrained by occasional peaks in the flow shear forces. Thus the sedimentation of solids is unlikely to cause detrimental effects under the turbulent conditions prevailing in the channel flow. On the other hand, the accumulation of contaminants at and above the suspension-air boundary at channel walls was deemed possible and should be controlled to avoid deposit formation problems. Similar effect of material build-up due to gradual contamination and deposit layering is fairly common e.g. in process tanks that are operated with a fairly constant surface levels but without washing showers or other means to keep the walls clean.

Turbulent mixing was seen to prevent sediment formation, but together with air entrainment near the discharge, it was seen to form a notable layer of foam on the channel flow surface, the effect being pronounced towards the end of the channel, where the flow settles. A similar effect is commonly noted in wire pits or white water silos (Weise et al. 1999, Haapala 2005), and thus de-foaming agents and water showers are widely used to control this froth formation. Froth formation could be further enhanced, however, and used to remove hydrophobic contaminants from white water by means of flotation. This adaptation of channel flow deaeration to white water purification forms the second part of the present thesis.

4.4 Summary of passive white water deaeration

The efficiency of passive channel flow deaeration is dependent on multiple factors that need to be taken into account when designing a deaeration process. The macro-scale flow properties affecting channel flow deaeration efficiency are the residence time and the turbulent mixing near the flow discharge, which can cause excess air entrainment. The accept gas content is also dependent on the rising of microbubbles in the white water, which differs between processes and can be described as bubble drag, to which both dissolved and dispersed suspension components contribute. Solid particles on the channel base may form a loose, movable sediment, but this should have no practical effect on the feasibility of operation of the deaeration process.

The pilot-scale experiments showed that not all process waters allow the same level of gas separation to be reached. All the suspensions tested were, capable of deaeration to entrained gas content below 0.5%, however, although practical limitations remained in particular cases. In view of earlier work on the
acceptable gas content at the wet end of a paper machine, the result indicates that the passive channel flow deaeration method can be applicable to many paper and board process configurations.

The analysis of microbubble dynamics showed that the most drag is caused by the excess hydrophobic components that stabilise the bubble surfaces and the dispersed particles that attach to the bubbles. A generalised experimental correlation was derived for the drag force experienced by small bubbles in a group of typical white waters. The drag model and the measured rise velocities of small bubbles in different white water samples can be used for modelling purposes and for designing tailored gas separation processes for different qualities of papermaking white water once their properties and the desired level of deaeration are known.
5 Purification of circulation water by selective flotation – adaptation to channel flow deaeration

This chapter addresses hypothesis 2 and presents the results regarding the flotation purification of white water. The efficiency and selectivity of the removal of detrimental substances by froth flotation and the losses of beneficial fibre fines and mineral fillers are discussed. The laboratory experiments are discussed in parallel with an analysis of a pilot scale process in which channel flow was used for deaeration and white water frothing.

5.1 Flotation as a means of purifying process water

Although the concept of white water flotation is not novel, it is commonly carried out in the form of dissolved air flotation (DAF) for process water and effluent clarification as a part of pulp preparation. Flotation has commonly been considered unsuitable for the paper machine loop due to the high rate of removal of all solids, including fillers and fibre fines (Røring & Wackerberg 1997, Richardson & Grubb 2004, Sarja 2007). Air has also commonly been taken out of the wet end and not fed in, and the frothing of white water can easily lead to problematic deposit formation, so that it is not considered beneficial in terms of water purification. Thus any froth that occurs is commonly dispersed with defoamer chemicals or mechanically by means of water showers (Allen et al. 1993, Stoor 2006, Helle 2007). Applications of flotation to the paper machine loop have consequently been scarce.

Recent studies involving the use of column flotation have discussed such an approach, but have as yet remained far from suggesting practical process applications (Dionne et al. 2007, Ricard et al. 2008, De Grado et al. 2010). Considerable benefits have been reported in terms of the web strength and optical properties of hand sheets made from white water fines following reduction of their ink and wood extractives content, and it has also been shown that fines and fillers become contaminated while circulating in the wet end, so that their removal can also be beneficial to some extent (Rundlöf et al. 2000a, b, Ricard & Dorris 2007). Thus it can be concluded that for any improvement in optical properties a balance will have to be achieved between removal of ink and losses of bright fillers (Ben et al. 2003, 2004).
Selective flotation as a method is widely used to remove contaminants from recycled paper during deinking (Holik 2000) and it has also been studied for pitch removal from mechanical pulps (Korpela 2006). A higher selectivity in the removal of hydrophobic contaminants, i.e. ink, stickies and wood extractives, can be achieved with this process than with DAF, which also removes vital fillers or wood fines (Sarja 2007, Körkkö et al. 2008).

White water may also have a tendency to produce sufficient froth to entrain and remove particles without flotation chemicals, due to the presence of calcium and surface-active extractives. Under such conditions selective flotation can be used to remove hydrophobic contaminants, at the expense of some removal of fibre fines and mineral fillers. With controlled froth removal this method would also make the use of defoamer chemicals unnecessary. As noted by Korpela (2006) and Ricard et al. (2008), the usability of flotation should become apparent in a multistage process where some of the removed solids can be returned to the process and the removal of contaminants can be made more efficient.

5.2 Frothing of white water

Distinct differences in the froth forming capabilities of white waters were noted in the experimental work belonging to this thesis. All the process waters from mill sites included some defoaming chemicals, and their chemical composition also varied substantially depending on the raw materials used in each process. Also the contaminant content and the composition of the contaminants varied, as did the efficiency of their removal by flotation. Thus generalisations from the results should be made with care, although the phenomenon depicted is similar for all types of process water.

5.2.1 Unaided frothing of white water

Froth formation in white water was investigated in Paper IV, where 20 L batches of white water of different origins were floated and tested to assess the efficiency and selectivity of contaminant and beneficial solid component removal. All the white water samples tested were able to produce a relatively stable froth layer in the flotation cell or channel flow when gas bubbles were introduced into the system, except for one water sample from an OCC mill which is described in detail in Paper IV. In this case the inability to generate foam could be attributed to extremely high water hardness and the absence of surfactants, as is typical of
OCC processes. This example serves to remind us that the process water properties differ greatly between mill sites and that over-enthusiastic generalisation may prove misleading.

The use of flotation chemicals would probably make all types of water produce froth, but that would not be a satisfactory result considering the location of white water frothing in the wet end, where additional chemicals are generally not desirable. On the other hand, the formation of a stable froth layer is the single most definitive physicochemical prerequisite for sustainable white water flotation.

The presence of calcium ions in a floated suspension is generally required for the collection of hydrophobic particles. The carbonate fillers that have accumulated in the white water typically provide a sufficient level of calcium ions capable of reacting with anionic surface-active compounds and precipitating them as solid particles. These are believed to be part of the collector system in deinking applications, although the exact mechanism of operation of such a system still remains unclear (Johansson et al. 1996, Costa & Rubio 2005). A certain amount of soluble surface-active compounds must nevertheless also be present to create a sustainable froth on top of the flotation cell in which floated materials can become suspended. These components are also found in great numbers in process water used with mechanical or recycled pulps, due, for instance, to the presence of deinking chemicals, coating colours and fines from recycled coated paper.

Froth stability can also be weakened by the presence of calcium soaps, possibly caused by an interaction between the calcium ions in the process water and fatty acids such as oleic acid originating from the wood fibres or the deinking chemicals. This defoaming effect of calcium and magnesium soaps is also well known in practice, but the theory of the phenomenon is not fully understood (Zhang et al. 2004, Lim 2009). In addition, the commonly used defoamer chemicals are likely to hinder froth formation. This aspect should also be considered when testing white water for its frothing capabilities. It is unlikely that a defoamer will be present if a selective flotation process is actively in use at the wet end of a paper machine.

5.2.2 Efficiency of contaminant removal

The selective flotation experiments reported in Paper IV and Haapala et al. 2010a examined the ink, stickies and wood extractives content of white water and the removal of these substances. As noted in the laboratory flotation experiments of Paper IV, the removal of components from recycled newsprint machine white
water (WW-DIP) differs slightly from the component removal in the case of virgin newsprint white water (WW-MP). In Haapala et al. (2010) contaminant removal was investigated in the form of a two-stage process where the first flotation phase took place in the deaeration channel and the second in a conventional flotation cell.

In general, a good level of reduction in the contaminant content of the white water was achieved. Removal was considered to be best for a number of extractives and stickies, all of which are known to be highly hydrophobic and efficiently removed by selective flotation (Korpela 2006, Sarja 2007). It was concluded that the most hydrophobic inks and toner particles are removed with relative ease during the first few minutes of flotation. This is shown in Fig. 18 and confirmed by visual observation of the froth build-up, where the colour ink residue was present and visible for no longer than a minute.

![Fig. 18. Ink content reduction and separation efficiency in the laboratory frothing of white water from a recycled paper process. Ink content was defined according to the sheet method presented in Haapala et al. 2008 and the removal efficiency as given in Eq. 3. The trend lines are indicative. (Modified from Paper IV, © Haapala et al.).](image)

A moderate level of ink removal can also result from fragmentation of the ink in the process water (Ricard et al. 2008), but this was not measured in the present investigation. The bulk of the ink particles circulating in the paper machine loop are constantly affected by stresses during pumping, screening and filtration through a fibre mat in the former. Most of the ink particles that remain in the water circulation are therefore likely to be very small in size. This supports the conclusion of Holík (2000) that most of the free ink in process water is below 10 µm, the size range that is reportedly poorly removed in selective flotation. The results differ slightly from those of the column flotation trials reported by Dionne et al. (2007), as they and Ricard et al. (2008) did not report any promotion of ink
removal as occurring in the early stages of flotation. This can be attributed to differences between inks and to the dynamic nature of column flotation, which does not allow separation of hydrophobic material at the air-water interface prior to the experiments as is the case in batch laboratory flotation.

The wood extractives and stickies were also removed very effectively, as determined by elution methods. As shown in Fig. 19, the efficiency of removal of all the extracted components was good with both white water samples tested, being slightly better with the virgin newsprint white water (WW-MP), where the initial concentration of wood extractives, 224 mg/g, was much higher relative to the total solids content than in the recycled pulp newsprint white water (WW-DIP), which contained only 20.3 mg/g of extracted components. These results include the stickies measured in the WW-DIP water, which initially made up 2.4 mg/g of the total contaminants. Despite the apparent need for their removal, no previous results have been reported on stickies removal from white water by selective flotation at the paper machine wet end.

The reductions in all the detrimental components measured in the WW-MP and WW-DIP samples are summarised in Table 4. Removal was highest for triglycerides and combined fatty acids and sterols in both cases, the removal of stickies was also considered good. Resin acids and ink particles were removed with reasonable efficiency but not as well as the other components studied.

Fig. 19. Efficiency of the removal of all extracted components, including wood extractives and stickies, from the white water of two newsprint paper machines. Values calculated according to the data of Paper IV.

The reductions in all the detrimental components measured in the WW-MP and WW-DIP samples are summarised in Table 4. Removal was highest for triglycerides and combined fatty acids and sterols in both cases, the removal of stickies was also considered good. Resin acids and ink particles were removed with reasonable efficiency but not as well as the other components studied.
Table 4. Reductions (%) in the concentrations of white water components in selective flotation. (Paper IV, © Haapala et al.).

<table>
<thead>
<tr>
<th>White water</th>
<th>Yield [%]</th>
<th>Ink Stickies</th>
<th>Triglycerides</th>
<th>Steryl esters</th>
<th>Fatty acids and sterols</th>
<th>Resin acids</th>
<th>Total extractives</th>
</tr>
</thead>
<tbody>
<tr>
<td>DIP newsprint</td>
<td>70</td>
<td>40</td>
<td>62</td>
<td>71</td>
<td>50</td>
<td>68</td>
<td>72</td>
</tr>
<tr>
<td>Virgin newsprint</td>
<td>70</td>
<td>na</td>
<td>na</td>
<td>53</td>
<td>45</td>
<td>46</td>
<td>50</td>
</tr>
</tbody>
</table>

The reductions in contaminant content achieved by channel flow flotation, as reported in Haapala et al. (2010a), were not quite as high as those obtained in the laboratory flotation cell due to the weaker froth build-up and shorter residence times. Separation in a secondary flotation cell, and the two-phase process as a whole, gave similar results to those summarized in Table 4, however. These are discussed further in section 5.3.

For reference purposes, reductions in stickies concentration in deinking flotation as reported in a study of eight mills varied from 48 to 81% (Sarja 2007), and when the separation was continued in a second flotation stage, with screening, cleaning, dewatering, etc., the total reductions in stickies varied from 74 to 92%. This indicates that considerable amounts of stickies are being carried over to the paper machine and that the removal of stickies from both pulp and water by selective flotation is good.

The total concentration of extractives in WW-MP was high relative to the WW-DIP when measured in terms of total extracts detected in untreated white water. This is common for mechanical pulps, as the pulping lines contain fewer cleaning stages than the deinking lines used for recycled fibres, as stated by MacNeil et al. (2004), whose results pointed to very good fatty acid removal in flotation, but poor resin acid removal from DIP furnish when investigating three deinking lines. Similarly, Korpela (2006) showed that up to 85% of total resin can be removed from mechanical pulp in laboratory flotation. These processes were nevertheless chemically aided to obtain maximum removal efficiency. Recent column flotation experiments with white water without chemicals but with extended treatment times of up to 11 minutes showed removal rates for dissolved and colloidal material of 73% (Ricard et al. 2008) and 85% (Dionne et al. 2007). The results of Paper IV show total extractives reductions of up to 65% and 50%.
for WW-DIP and WW-MP, respectively. These appear to be in line with the earlier investigations, given the shorter flotation times used.

Removal rates in all the white water schemes can be considered good, given the short treatment times and lack of flotation aids. Our results indicate that flotation removal promotes the removal of triglycerides slightly more efficiently than the other extractive groups, probably due to their near-insoluble nature and the quite high solubility of resin acids, even in hard water (MacNeil et al. 2010). In the case of WW-DIP, fatty acids and sterols also had a better removal rate than resin acids or steryl esters. As the differences between the extractives components were relatively minor, practical conclusions from the papermaking point of view can be drawn from the removal of total extracts. These are easier to analyse as a group and still provide sufficient information on the performance of the separation processes.

5.2.3 Selectivity in the removal of contaminants

The flotation efficiency for each contaminant group was evaluated via the selectivity index $Q_N$ presented by Nelson (1981), as given in Eq. (4). As a example of this, the ink removal efficiency and its index of selectivity (Paper IV) are shown in Fig. 20. The removal selectivity of the detrimental component groups studied was estimated in laboratory flotation (Paper IV) and in the two-stage separation process (Haapala et al. (2010a)), the level of selectivity in the larger-scale process proving similar to that in the laboratory frothing experiments but not quite as good, due to weaker froth formation and particle entrainment in channel flow froth. This matter is discussed further in section 5.3, along with the analysis of the process efficiency.
The selectivities of all the contaminants removed are summarised in Table 5. The results show that all the components quantified as contaminants are selectively removed in respect to cellulosic pulp components and mineral fillers, the highest selectivity, 0.87, being obtained for stickies, triglycerides, fatty acids and sterols. The selectivities of the components were similar in both white water samples, although the removal of fatty acids and sterols showed a higher selectivity from the WW-DIP than from the WW-MP. For all the other components the differences were within the limits of measurement accuracy. The resin acids had the lowest selectivity of all the components. The stickies and ink that are present in practically all recycled pulp processes were also removed with good selectivity.

Table 5. Selectivity indices for white water contaminant removal. (Paper IV, © Haapala et al.).

<table>
<thead>
<tr>
<th>White water</th>
<th>Ink</th>
<th>Stickies</th>
<th>Triglycerides</th>
<th>Steryl esters</th>
<th>Fatty acids and sterols</th>
<th>Resin acids</th>
<th>Total extractives</th>
</tr>
</thead>
<tbody>
<tr>
<td>DIP newsprint</td>
<td>0.74</td>
<td>0.87</td>
<td>0.87</td>
<td>0.78</td>
<td>0.87</td>
<td>0.63</td>
<td>0.79</td>
</tr>
<tr>
<td>Virgin newsprint</td>
<td>na</td>
<td>na</td>
<td>0.83</td>
<td>0.76</td>
<td>0.75</td>
<td>0.69</td>
<td>0.77</td>
</tr>
</tbody>
</table>

A previous study of the deinking flotation of pulps (Körkkö et al. 2008) has shown that the selectivity of component removal decreases in the following order: ink, fibre fines, ash, short fibres and finally long fibres. While the selectivity of ink was fairly high in our case, obtaining an index of 0.74, considerably higher
selectivity was shown by stickies and wood extractives (0.87), excluding the resin acids, the analysis of which entailed some sources of uncertainty.

Sarja et al. (2007) reported that stickies are removed faster than ink or at the same rate in pulp deinking flotation, and the results presented in Paper IV that indicate that stickies are readily removed from white water by frothing are in line with this. In another previous study, Korpela (2006) reported that typical pitch components are all removed at the same rate in flotation. In our case, only steryl esters ($Q_N$ 0.76–0.78) and resin acids ($Q_N$ 0.63–0.69) deviated from the other wood components. As a group, the wood extractives had fairly high selectivity and all the components tested could be said to have had a selective manner of removal. The good selectivity obtained for component removal indicates that even a brief flotation and low froth removal can result in a considerable removal of contaminants.

One essential aspect when analysing separation selectivity is to be aware of the other components that are removed in addition to the contaminants. As is always the case in flotation, some valuable material such as fibres and minerals will be lost in the froth, which will lower the yield and reduce the profitability of the process. In industrial processes such solid losses are controlled via soap addition, the air-to-water feed ratio, froth layer height and froth washing, for instance. The surfaces of filler components in deinking processes are considered to be more susceptible to hydrophobic contaminants, and thus their removal can be justified by the gains in optical pulp properties (Carré et al. 2001, Røring et al. 2002, Ben & Dorris 2004). In addition, the highest total losses come from the mineral fillers and to some extent from the fibre fines (Carré et al. 2001, Røring et al. 2002, Körkkö et al. 2008). Fibre component losses have been reported to occur linearly in relation to the volume of water removed in flotation (Ajersch & Pelton 1996). Since the fibres and fibre fines are hydrophilic in nature, it has been suggested that calcium-precipitated sticky particles can attach to them and assist in their removal, especially where fine particles are concerned (Drabek et al. 1998). Also, contamination of fines and fibres makes their surface more hydrophobic and favours their entrainment in the froth (Rundlöf et al. 2000a, b, Ricard & Dorris 2007).

The losses of fibre fines and fillers accumulate rapidly to levels that are not appropriate for practical papermaking operations unless some of the components removed can be returned to the process. Hence, as is usual in flotation processes, the losses of solids and the final removal efficiency at the component level can be achieved more easily by arranging a secondary flotation stage in a cascade mode.
Also, as pointed out by Ricard et al. (2008), even a partial treatment of white water by some purification method or other will remove unwanted components and provide beneficial effects.

5.3 A two-stage process arrangement for white water frothing

The addition of a selective flotation function to channel flow deaeration was investigated in Haapala et al. (2010a) with two individual pilot-scale setups, analysing the combined process via mass balances, as described in section 3.2.2. Haapala et al. (2010a) contains a case study of two newsprint white water samples: DIP from a paper machine using only RCF pulp and TMP/DIP from a paper machine using both recycled and virgin stock. The general observations related to process performance are assumed to apply also to other process waters provided they are able to produce froth, as described in section 5.2.

The study consisted of analyses of entrained gas separation, channel flow frothing and contaminant separation efficiency, secondary flotation efficiency and a consideration of the applicability and efficiency of the total process for separating dispersed contaminants. The selectivity of separation was also assessed briefly at each stage in the process. The studies of the channel flow loop are presented in section 5.3.1, secondary loop flotation is discussed in section 5.3.2 and the combined process of white water deaeration and purification is summarised in section 5.3.3.

5.3.1 Channel flow frothing and deaeration

Froth formation and the feasibility of purifying the circulation water by rejecting the channel flow overflow were investigated by inducing froth formation only by means of gas entrainment (turbulent mixing of the channel flow as discussed in section 4.3), and in the second case by intensifying the effect by means of an added gas feed through the membrane foils. The process is illustrated in Fig. 8, page 37.

Froth build-up in the channel flow was observed visually to be quite weak without any added aeration, but in every case the DIP water produced quite a stable froth and in a greater quantity than was obtained with the TMP/DIP water. Froth formation led in both cases to a concentration of total solid material in the froth,
and this effect was especially pronounced in the batches subjected to additional aeration.

The removal of contaminants including inks, stickies and wood extractives from the white water through the channel flow surface froth and the overflow water fraction was calculated according to Eq. 3, the removal efficiencies being related to the losses of solids and water. Selectivity indices were also produced for each component removed, although the amount of data available leaves the results no more than indicative. The results for channel flow flotation are summarised in Table 6. The 60% removal efficiency quoted for stickies from DIP newsprint water is probably due to an error in sampling or analysis, however, as it is very unlikely to represent the actual process. The correct value would probably be around 20%.

Table 6. Removal efficiency of contaminants and reject rates in the channel flow frothing stage. (Modified from Haapala et al. (2010a), © Haapala et al.).

<table>
<thead>
<tr>
<th>Channel flow frothing mode</th>
<th>TMP/DIP newsprint</th>
<th>DIP newsprint</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>without aeration</td>
<td>with aeration</td>
</tr>
<tr>
<td>Ink removal eff. [%]</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>THF extractives removal eff. [%]</td>
<td>14</td>
<td>21</td>
</tr>
<tr>
<td>Stickies removal eff. [%]</td>
<td>11</td>
<td>20</td>
</tr>
<tr>
<td>Ash removal eff. [%]</td>
<td>12</td>
<td>14</td>
</tr>
<tr>
<td>RRV [%]</td>
<td>9.8</td>
<td>10.6</td>
</tr>
<tr>
<td>RRM [%]</td>
<td>10.8</td>
<td>12.5</td>
</tr>
</tbody>
</table>

1 The efficiency of stickies removal from DIP newsprint water with channel flow aeration as measured in Haapala et al. (2010a) was 60%. This differs considerably from the trend in separation efficiency seen during the experiments, however, indicating that the result is likely to be biased, either due to the sampling or the analysis. Hence a more conservative removal efficiency of 20% is used here for the assessment of process efficiency.

A higher removal of contaminants was consistently seen in the batches subjected to air feed into the channel flow, but the selectivity of contaminant separation in channel flow frothing was poor by comparison with the laboratory trials. The Q-index for wood extractives and stickies removal was at best around 0.4, while the removal of ink showed in practice no selectivity whatsoever. The gas entrainment that was seen to be problematic when gas separation was considered apparently does not provide the optimal amount of gas for froth formation that would be efficient for entrapping contaminants. The air feed used here clearly improved component separation, and it is reasonable to assume that optimization of the air-
to-flow ratio would have a potential for better removal efficiency. It would also be possible to separate only the froth layer out for further treatment instead of the whole channel flow overflow in order to further minimise the volumes to be processed.

Although the effect of water purification on paper quality was not investigated here, previous studies indicate that the 15% decrease observed in ink content and the 13 to 21% decrease in wood extractives content can have a significant impact on paper strength and optical appearance (Sundberg et al. 2000, Holmbom & Sundberg 2003, Ricard et al. 2008). Similarly a stickies removal of around 20% can be considered beneficial. The use of such a channel flow configuration alone, however, would result in solids losses of up to 10 to 15%, which can be considered unsustainable in terms of process economics.

The residual gas content after channel flow deaeration was measured during the trials as being 0.3% for TMP/DIP white water and 0.4% for DIP white water. The analysis showed that the feeding of sufficiently large bubbles into the beginning of the channel flow has no effect on deaeration performance. The results are in line with earlier analyses, the higher gas content in the DIP water being attributed primarily to its higher solids content.

### 5.3.2 Secondary flotation

Secondary flotation was carried out differently for each type of white water, the trials with the TMP/DIP water being performed in the flotation cell in a manner targeting low solids losses, while for the DIP water the mode of flotation control was changed to allow a greater removal of froth. A substantial removal of wood extractives and stickies was achieved with a higher DIP water reject rate. The removal efficiencies of the secondary flotation stage are given in Table 7, and the secondary flotation process is illustrated in Fig. 8.
Table 7. Removal efficiency of contaminants and reject rates in the second flotation stage. (Modified from Haapala et al. (2010a), © Haapala et al.).

<table>
<thead>
<tr>
<th>Channel flow frothing mode</th>
<th>TMP/DIP newsprint</th>
<th>DIP newsprint</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>without aeration</td>
<td>with aeration</td>
</tr>
<tr>
<td>Ink removal eff. [%]</td>
<td>17</td>
<td>18</td>
</tr>
<tr>
<td>THF extractives removal eff. [%]</td>
<td>12</td>
<td>18</td>
</tr>
<tr>
<td>Stickies removal eff. [%]</td>
<td>36</td>
<td>28(^1)</td>
</tr>
<tr>
<td>Ash removal eff. [%]</td>
<td>12</td>
<td>10</td>
</tr>
<tr>
<td>RRV [%]</td>
<td>2.3</td>
<td>1.0</td>
</tr>
<tr>
<td>RRM [%]</td>
<td>8.8</td>
<td>7.3</td>
</tr>
</tbody>
</table>

\(^{1}\) The stickies content was obtained by assuming the separation efficiency of the channel flow stage to be 20%.

It was observed that wood extractives and stickies were in general separated with a much better efficiency in cases where frothing in the channel flow was first enhanced by adding aeration to the channel flow. The use of an air feed slightly increased the relative solids losses, indicating that more material was being driven from the liquid phase into the froth. In addition, the treatment time in the secondary flotation was markedly higher than in the channel flow flotation, which enabled a thicker, more solid froth to build up.

The higher reject rate in DIP water resulted in a higher removal of contaminants, reaching 40 to 55% for wood extractives and 70 to 90% for stickies, depending on whether or not the treated water was enriched by means of channel flow aeration. TMP/DIP water extractives were reduced by less than 20% and stickies by less than 30%. The removal of ink was less pronounced relative to the mass reject ratio.

Naturally pulps from recycled paper are purified by flotation or washing as a part of pulping before the addition of papermaking additives where there are no losses of such additives during the purification. However, as these processes are never 100% efficient there will always be some carry-over to the paper machine loop where further treatment may prove beneficial, even at the cost of losses in fines, fillers and some process chemicals.

The selectivity of extractives and stickies separation, as assessed in terms of the \(Q\)-index, was markedly better than in channel flow flotation. The \(Q\)-Index for stickies removal was around 0.80 for water not treated by air feed to the channel flow, and around 0.90 when added aeration was used. Similarly, the selectivity for extractives was seen to improve from a \(Q_N\) of around 0.30 up to 0.65, depending
on the channel flow frothing mode. The selectivity of ink removal also behaved in a comparable manner, being approximately 0.50 and 0.65.

The results appear to be in line with previous work on white water flotation (Dionne et al. 2007, Ricard et al. 2008) and effluent treatment in DAF flotation (MacNeil et al. 2004, Perrin & Julien Saint Amand 2006, Sarja 2007), although comparison with DAF is problematic due to its characteristic of removing as much solid material as possible, which was to be minimised here. The air feed ratio and the achieving of sufficient separation in the first stage both clearly contribute to the separation efficiency of the second stage, and hence to the total process. The management of secondary flotation was fairly easy and it ensured a substantially longer residence time for the water, and fairly high separation efficiency and selectivity with regard to the contaminants. The parameters of flotation cell operation are also well established, while froth formation in the channel flow in parallel with functioning deaeration still needs further investigation.

5.3.3 Total process efficiency assessment

The total effect of contaminant removal in channel flow and secondary flotation was assessed in terms of mass balances based on a forward-connected cascade system, as shown in Fig. 10 at page 39, and the efficiencies achieved in component separation. The losses that this system would inflict in the form of solids and water were also calculated. A summary of the results is presented in Table 8.

Table 8. Total removal efficiency and reject rates of the removal of detrimental materials and losses in the simulated two-stage white water frothing process. (Modified from Haapala et al. (2010a), © Haapala et al.).

<table>
<thead>
<tr>
<th>Channel flow frothing mode</th>
<th>TMP/DIP newsprint</th>
<th>DIP newsprint</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>without aeration</td>
<td>with aeration</td>
</tr>
<tr>
<td>Ink removal eff. [%]</td>
<td>2.5</td>
<td>2.6</td>
</tr>
<tr>
<td>THF extractives removal eff. [%]</td>
<td>1.7</td>
<td>3.7</td>
</tr>
<tr>
<td>Stickies removal eff. [%]</td>
<td>4.0</td>
<td>5.5¹</td>
</tr>
<tr>
<td>Ash removal eff. [%]</td>
<td>1.4</td>
<td>1.3</td>
</tr>
<tr>
<td>RRV [%]</td>
<td>0.2</td>
<td>0.1</td>
</tr>
<tr>
<td>RRm [%]</td>
<td>0.9</td>
<td>0.9</td>
</tr>
</tbody>
</table>

¹The stickies content was obtained by assuming the separation efficiency of the channel flow stage to be 20%.
Total losses remained significantly lower in the case of TMP/DIP water treatment than in that of DIP water due to the differences in secondary flotation. Even with a very low total reject rate of around 1% for TMP/DIP solids, with a mere 0.1% of the water wasted, the system could continuously remove 5% of the ink, 4% of the extractives and 6% of the stickies from the white water loop. For the DIP water, where the reject rates were slightly higher, 2.8% and 5.5% for water and solids, respectively, there was a continuous removal of 7% of ink, 10% of extractives and 21% of stickies.

The rates of contaminant removal indicate good separation selectivity even without flotation chemicals. The $Q_N$ indices for contaminant removal in the total process were 0.2 to 0.3 for ink, 0.3 to 0.7 for extractives and 0.6 to 0.8 for stickies. These are somewhat crude estimates due to the low number of samples available, but they do indicate that the selectivity results obtained in laboratory flotation can also be achieved in large-scale processes.

It is also apparent that the total contaminant removal rates are closely related to the mode of operation and reject rates employed in secondary flotation. These must be optimized individually, based on the water purification target, the available process volumes and the amount of reject that can be removed from both flotation stages. The functionality of both deaeration and flotation is greatly affected by the residence time of the water in each unit process, and hence the limits of the efficiency of this arrangement tend to originate from external sources.

5.4 Summary of white water purification

The observed frothing of white water in the laboratory flotation cell and in the pilot-scale channel flow was used to separate out the white water contaminants that had been found to cause adverse effects on production and process quality in the paper machine. Some forms of process water proved unable to produce stable froth, which is the single prerequisite for the process to operate.

The reduction in contaminant content and the selectivity of their removal was good in most cases without any added flotation chemicals. Channel flow with an overflow can be considered well suited for this task, and further treatment of the channel flow reject in a secondary flotation was considered beneficial. The secondary flotation schemes can be run with low solids losses to the whole system while continuously rejecting contaminated solids and dispersed contaminants from the system.
The highest removal rate and selectivity was observed for hydrophobic stickies and wood extractives, but ink was also well removed. A large fraction of the solid components can be returned to the process stream while continuously removing the contaminants, although some level of losses in terms of fibre fines, fillers and process water must be expected. The feasibility of the added process complexity and losses in solid components should arise from the extended uptime, increased runnability and improvements in product quality. The quantity of solids losses can be related to the amount and dry matter content of the froth removed, which can be adjusted by reject ratios. Based on our favored scenarios, 55 to 70% of total losses can be considered originating from minerals and the rest from cellulosic materials.
6 Conclusions

Channel flow deaeration provides an option for deaerating and purifying paper machine white water in processes where total gas separation is not required. The aim of this thesis was to analyse the efficiency and applicability of a channel flow design for white water deaeration and to study the dynamics of passive bubbly gas removal. In addition, selective separation of detrimental white water components during gas removal was studied as a means of adding further functionality to the channel flow design.

As stated in hypothesis 1, the properties of white water in individual cases notably affect deaeration performance in relation to pure water, from which all entrained air is easily removed in open channel flow. The pilot-scale studies showed that the same level of gas separation cannot be reached with all forms of process waters, although quantification showed that all the suspensions tested were able to achieve a bubble gas content of less than 0.5% in channel flow deaeration, in spite of case-specific practical limitations depending on white water properties. Based on earlier work on the acceptable gas content in the wet end of a paper machine, the results indicate that the method of passive channel flow deaeration presented here is applicable to many paper and board process configurations.

The macro-scale properties affecting channel flow deaeration efficiency include flow intensity, residence time and the viscous suspension properties that influence bubble motion. Moreover, the turbulent mixing at the flow discharge and the consequent air entrainment were considered to be the crucial factors that have a profound impact on channel flow deaeration efficiency and should be minimised.

The gases remaining in the system after the passive deaeration process consist of small microbubbles that are unable to escape from the flow in the given time due to their slow rise velocity in process water. This is a consequence of elevated microbubble drag caused by hydrophobic contamination of the bubble surfaces and solid components attached to the bubbles. Hence gas separation can in general be expected to be more difficult in the case of process water that has mechanical or deinked pulp as its raw material than in those from wood-free fine paper processes, for example. The experimental correlations for the bubble dynamics were derived in both cases on the basis of experimental data, providing new information on the drag force experienced by small bubbles in white water.
This can be used to model and design tailored gas separation processes for different papermaking processes.

Since hydrophobic contaminants have been found to cause substantial adverse effects on paper machine production and process quality, the frothing of white water in a channel flow was investigated in parallel with passive deaeration in order to separate these contaminants from the paper machine wet end. 

Hypothesis 2 was proved correct in laboratory experiments and pilot studies showing that good selective removal is attainable by the flotation of white water. 

The use of flotation as a process water purification method requires a reconsideration of the usage of anti-foaming agents in the paper machine circulation. Channel flow with an overflow was considered well suited for froth separation, with benefits to be obtained from further treatment of the channel flow reject in a secondary flotation. As a result, a large fraction of the solid components could be returned to the process stream while continuously removing contaminants, e.g. ink, stickies and wood extractives, although a certain level of losses in fines and fillers must be expected.

The published results are the first to present a chemically unaided white water flotation method and a quantification of its efficiency, taking into account the low level of solid losses that can be achieved. The high inherent selectivity of the removal of stickies and wood extractives in flotation indicates that selective flotation can be applicable in the wet end. In the light of these investigations, our present understanding is that internal purification of white water has a potential to generate considerable benefits for papermaking processes, providing an increase in production time, higher sheet quality and a reduced web breakage rate, for instance.

The proposed multifunctional process, channel flow deaeration and the frothing of white water, was seen as straightforward, economical and feasible, while also providing benefits in terms of total process efficiency that are not obtainable with any current process scheme. The experimental parameters for bubble dynamics and flotation efficiency presented here can be used to better model these processes and to simulate the process flows based on mass balances.

The subject of this thesis is a broad one, however, and many practical areas call for supplementary investigations. Future work should include the optimisation of the white water flotation parameters, minimisation of gas entrainment in the early stages of channel flow and further processing of the resulting froth waste. The channel flow design would also benefit from a study that relates the motion of bubbles and solid particles to the level of flow.
turbulence as the conditions should be optimised for the buoyant bubble rise while avoiding the unwanted solids sedimentation. Many aspects related to bubble motion in model white waters with controlled physicochemical properties, different fines and cellulosic components remain to be studied. Effects related to minor addition of surfactants and other flotation aids to white waters, especially in the secondary stage of flotation, should be investigated.

Some mechanisms of froth formation remain unknown and e.g. phenomena related to white water hardness, froth stability and other bubble-particle interactions are still under debate in the scientific community. More detailed knowledge of such matters would also benefit the conventional deinking flotation process development. Work with complex process waters gives realistic and case sensitive image on the actual mill conditions and how the studied processes can be expected to perform. On the other hand, the presence of multiple variables within the system that cannot be controlled or studied individually may limit the specific understanding of the effects of some factors. Thus there is ample room also for work made with simple, controlled model suspensions with known content of contaminants and other components. These allow for better repeatability of experiments, broader utilisation of statistically designed experiments and regression models, and more straightforward evaluation of the observed causal relations. This thesis presents a framework in which to study these effects further in pursuit of an optimised low-cost solution for internal white water treatment.
References


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Kolari M (2003) Attachment mechanisms and properties of bacterial biofilms on non-
living surfaces. Dissertation, University of Helsinki, Finland.

Korpela A (2006) Removal of resin from mechanical pulps by selective flotation:
and Technology 26(2): 175–186.

Krishna R, Urseanu MI, Baten JMV & Ellenberger J (1999) Wall effects on the rise of
single gas bubbles in liquids. International Communications in Heat and Mass
Transfer 26: 781–790.


Kyllönen HM, Pirkonen P & Nyström M (2005) Membrane filtration enhanced by


Laari A, Haapala A, Stoor T & Turunen I (2007) Simulation of entrained air separation
from paper machine circulation water using CFD. Proceedings of European Congress
of Chemical Engineering (ECCE-6), Copenhagen, Denmark.

Laari A, Haapala A & Turunen I (2010) Gas separation from paper machine white water in
open channel flow: Comparison of PIV measurements to CFD simulations. 19th
International Congress of Process and Chemical Engineering CHISA 2010 & 7th
European Congress of Chemical Engineering (ECCE-7), Prague, Czech Republic.

University of Technology.

Lahtinen T, Kosonen M, Tiirila M, Vuento M & Oker-Blom C (2006) Diversity of
bacteria contaminating paper machines. Journal of Industrial Microbiology &
Biotechnology 33(9): 734–740.


of TAPPI Newsprint Forum, Birmingham, Alabama, USA.


Jeandet P (2000) On the velocity of expanding spherical gas bubbles rising in line in
supersaturated hydroalcoholic solutions: Application to bubble trains in carbonated

264.


Lindsay JD, Ghaasiaan SM & Abdel-Khalik SI (1995) Macroscopic flow structure in a
bubbling paper pulp-water slurry. Industrial & Engineering Chemistry Research 34:
3342–3354.


Original papers


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Antti Haapala

PAPER MACHINE WHITE WATER TREATMENT IN CHANNEL FLOW

INTEGRATION OF PASSIVE DEAERATION AND SELECTIVE FLOTATION