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CHARACTERISATION AND REMOVAL OF GAS IN PAPERMAKING

Doctoral Thesis

Topi Helle

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Supervisor	Professor Hannu Paulapuro

Abstract

The objective of this dissertation was to characterise gas in papermaking and to study the effects of centrifugal force on flotation fibre recovery and the removal of gases from fibre suspensions. In order to reach these goals, laboratory and pilot paper machine trials with dispersed and precipitated gas bubbles were carried out. Laboratory and mill trials subjecting the fibre suspension to centrifugal force were also made.

Entrained gas bubbles had mostly adverse effects on papermaking, which was to be expected from previous studies reported in the literature. Even quite low entrained gas contents were found to affect papermaking. Precipitated gas bubbles appeared to have largely the same effect on papermaking as dispersed gas bubbles. However, differences were found in their effects on tear and wet tensile strength.

In this study, centrifugal force was found to remove gas bubbles effectively, so it can be used to remove gas from a papermaking fibre suspension. Centrifugal force did not remove dissolved gas effectively, but with correct process design sufficient removal of entrained air should be enough. In addition, it is possible to remove dissolved gas with centrifugal force with the help of turbulence or vacuum. According to the results in this study, centrifugal force cannot be used to improve flotation fibre recovery.

Keywords papermaking, gas, air, degassing, deaeration, flotation	
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Tiivistelmä

Väitöskirjan tavoitteena oli selvittää kaasujen käyttäytymistä paperinvalmistuksessa sekä tutkia keskipakovoiman vaikutusta kuitujen flotaatiotalteenottoon ja kaasujen poistoon kuitususpensiosta. Tavoitteen saavuttamiseksi tehtiin dispergoiduilla ja saostetuilla kaasukuplilla laboratorio- ja koepaperikonekokeita. Lisäksi kuitususpensiolle tehtiin laboratorio- ja tehdaspaperikonekokeita, joissa käytettiin keskipakovoimaa kaasun poistossa.

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Asiasanat paperinvalmistus, kaasu, ilma, ilmanpoisto, kaasunpoisto, flotaatio

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PREFACE

The research work reported in this thesis was carried out mainly in the Laboratory of Paper Technology at the Helsinki University of Technology and KCL Oy during 1997-2006. The work was financed for the most part by the Academy of Finland, the National Technology Agency (TEKES) and the Finnish Natural Resources Fund (Suomen Luonnonvarain Tutkimussäätiö), for which I am most grateful.

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Espoo, January 2007 Topi Helle

LIST OF PUBLICATIONS

This dissertation consists of five publications and their summary.

I. *Helle, T.-M.,* Effect of centrifugal force on flotation of air bubbles on to fibres and fillers, Paperi ja Puu 4(2000)82, 251-254

II. *Helle, T.-M., Meinander, P., Paulapuro, H.,* Removal of entrained air from white water by application of centrifugal force, Paperi ja Puu 5(1998)80, 379-382

III. *Helle, T.M., Meinander, P.O., Nykänen, R., Molander, K., Paulapuro, H.*, Air removal mill trials with the Pomp deaerator, Tappi Journal 6(1999)82, 146-149

IV. *Helle, T.-M.,* Qualitative and quantitative effects of entrained gas on papermaking, Paperi ja Puu 7(2000)82, 457-463

V. *Helle, T-M., Paulapuro, H.,* Effect of precipitated gas bubbles in papermaking, Appita Journal 6(2004)57, 444-447

AUTHOR'S CONTRIBUTION

I All experimental work, analysing the results and writing the original article.

II, III Designing the experiments, conducting the gas measurements, analysing the results and writing the final article.

IV Designing the experiments, analysing the results and writing the original article.

V Designing the experiments, analysing the results and writing the final article.

CONTENTS

1. INTRODUCTION

Gas has many detrimental effects on paper properties and papermaking processes, such as foam, spots, pinholes, pressure pulsations in the paper machine's approach flow system as well as impaired formation and drainage /1,2,3/. Therefore, gas is usually removed mechanically or chemically from the papermaking furnish. However, gas can be used in microflotation to recover fibres, fines and pigments from the white water leaving the paper machine.

The studies found in the literature have concentrated on the qualitative effects of gas on papermaking /2,3/. The quantitative effects of gas are important to know when new processes are designed and old processes are modernised, to be able to assess the need for gas removal. In this thesis work, both the qualitative and quantitative effects were studied in a pilot paper machine trial. In addition, in most studies gas bubbles have been made from dispersed gas. Therefore, also a laboratory study with precipitated gas bubbles was made to find out if precipitated bubbles behave differently from dispersed gas bubbles.

The effect of centrifugal force on gas bubbles and flotation was studied in laboratory. The target was to find out if centrifugal force can be used to remove gas in papermaking and to improve flotation fibre recovery. Fast fibre recovery and gas removal with small circulation water volumes should enable a faster response to changes in stock composition and process parameters. This would allow better control of production and product quality /4/. The improved flexibility of production would be especially advantageous in connection with paper grade changes.

2. OBJECTIVES AND STRUCTURE OF THE STUDY

The objective was to characterise the effects of gas on papermaking in the wet end of a paper machine An important goal was also to study the effects of centrifugal force on flotation fibre recovery and on the removal of gases from the fibre suspensions. The focus of the thesis was on papermaking technology, so the effects of microbiology and surface chemistry were not investigated in detail. The study was sub-divided into four objectives:

1. Reviewing the current knowledge related to gas in papermaking, including flotation fibre recovery and gas removal from fibre suspensions.

2. Developing a laboratory flotation device and a method to study the effects of centrifugal force on flotation and the removal of gases from fibre suspensions.

3. Examining the removal of entrained gas from white water by application of centrifugal force in paper mill trials.

4. Examining the effect of entrained and precipitated gas on papermaking to predict the need for deaeration on commercial paper machines.

The approach used in the experimental work was based on the following hypotheses:

1. Flotation fibre recovery can be significantly improved with the centrifugal force.

2. Gas can be removed effectively enough from the papermaking fibre suspension with centrifugal force.

3. Complete gas removal is not needed in papermaking.

This thesis is based on five original publications and a summary of them. The objectives of the thesis are addressed in the publications, as shown in Table 2.1. The five publications referred to in the text by Roman numerals are the following:

I. *Helle, T.-M.,* Effect of centrifugal force on flotation of air bubbles on to fibres and fillers, Paperi ja Puu 4(2000)82, 251-254

II. *Helle, T.-M., Meinander, P., Paulapuro, H.,* Removal of entrained air from white water by application of centrifugal force, Paperi ja Puu 5(1998)80, 379-382

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Table 2.1. Objectives of different publications.

	Publication				
Objective	**I**	**II**	**III**	**IV**	**V**
1	**X**			**X**	**X**
2	**X**				
3		**X**	**X**		
4				**X**	**X**

3. GAS IN PAPERMAKING

The gas present in the papermaking process consists of normal air, water vapour and various gases produced by microbiological and chemical reactions in the paper machine’s water circulation, such as decomposition of calcium carbonate pigments into carbon dioxide at acid pH /5,6/. The different gases dissolve in fibre-water suspension at concentrations related to their solubility. In this thesis work, air refers to any gas which is present in the papermaking stock.

In fibre suspensions gas exists in three forms: free gas, bound gas and dissolved gas. Free gas consists of large gas bubbles, which tend to rise to the surface as foam. Free gas can also become bound to fibres through mechanical action such as pumping. Bound gas consists of small gas bubbles, which are tightly attached to fibres and attract fibres to form fibre bundles. Free and bound gas are together called entrained gas. Dissolved gas has no effect on the fibre suspension’s physical characteristics, as long as the gas remains dissolved. It can precipitate into free and bound gas if the temperature and pressure of the fibre suspension change, which may occur in normal papermaking conditions /1,7,8/.

The diameters of most air bubbles measured by Isler and Widmer from photomicrographs in a papermaking furnish were from 30 to 170 µm, when the temperature was from 20 ^{o}C to 68^{o}C. The distribution was Gaussian but skewed. Not very small bubbles, with a diameter below 10 µm, were found, whereas larger bubbles up to 300 µm in diameter were found /9, 10/.

3.1. Effects of gas in papermaking

The adverse effects of entrained air and other gases are qualitatively well known and there are several studies on the qualitative effects of gas on papermaking /2,3,8,11,12/. Gas has been reported to have many detrimental effects on paper properties and papermaking processes. The most common effect of gas is surface foam, which causes foam spots in the sheet. Furthermore, sheets formed from stock with a high gas content are more porous and have lower density. Also, both wet web strength and dry strength are lower than for sheets formed from deaerated stock. Gas bubbles cause pinholes and collect hydrophobic substances on their surface. If these bubbles dissolve, the collected material can cause spots and deposits. Gas can also reduce the drainage rate on the wire and lead to poorer formation. In addition, gas in the fibre suspension causes energy losses in pumps and pressure pulses in the paper machine approach flow system /1,13/.

The design of the paper machine former influences the gas content and the effects of gas in papermaking. Twin-wire machines have been reported to have higher entrained gas contents than Fourdriner machines. However, twin-wire machines can very often have higher gas contents than Fourdriner machines, without having an influence on the paper machine due to the strong drainage /14/. /15,16/.

Chemical and biological slime builds up in various places of the process piping and chests. Chemical slime can be produced of chemical additives used in the process and biological slime can be attached to chemical slime. Biological slime grows rapidly if conditions are favourable for microbiological growth. Very often the pH is close to neutral and the temperature around 40°C in the papermaking process, which is favourable for biological slime growth. A high amount of air promotes biological slime growth /17/. Slime can cause smell and corrosion problems and also spots and deposits, which may result in wire plugging and even web breaks on the paper machine /17,47/.

The studies found in the literature have concentrated on the qualitative effects of gas in papermaking. In the experimental part of this study the quantitative effects of gas are discussed in detail.

3.2. Methods for measuring gas content

An expansion method for gas measurement (Boadway method) is often used to measure air or gas in a fibre suspension. The measurement is based on Boyle’s ideal gas law, equation 1.

$$p_0 \cdot V_0 = p_1 \cdot V_1, \qquad (1)$$

where V_0 is the initial volume, V_1 is the final volume, p_0 is the initial pressure and p_1 is the final pressure. When the sample is subjected to reduced pressure, the relative change in the volume is equal to the relative change in the amount of gas, because the volume of the liquid is almost independent of the pressure, Equation 2.

$$i = \frac{\Delta V}{V} \cdot 100\ \%, \qquad (2)$$

where i is the percentage of gas by volume, ΔV is the increase in volume and V is the volume of the sample chamber. The samples are taken at atmospheric pressure and then expanded at 0.5 bar. This method can be used to measure all types of gas, i.e. both entrained and dissolved gas /18/.

The amount of gas can also be measured with the compression method. Equation 2 also applies if the pressure is increased. Of course, in this case the volume will decrease instead of increasing. Other methods to determine gas content are based on measuring the density of the sample /19/, the attenuation of ultrasound in the sample /15/ and a sonar measurement /20/. All these methods determine the amount of entrained gas; the expansion method can also be used to measure the amount of dissolved gas.

The above methods are used to measure gas manually. On-line measurement is also possible. The Sonica on-line gas content meter is based on the attenuation of ultrasound. The normal measurement of entrained gas is performed with ultrasound, but the calibration is done with the compression method. The Sonica meter is widely used at mills.

In the sonar measurement method the gas content is determined by measuring the speed of sound, or the speed at which sound propagates through the process medium /20/. Sonar measurement is done on-line based on an array of sensors that listen to and interpret noise generated by the process machinery and flow, which are present in all industrial processes. The air percentage is then calculated directly from the measured speed of sound. The sensors are clamped onto the pipe and there are no parts in direct contact with process fluids /21/.

Other on-line measuring meters are usually based on expansion or compression methods, and include the Dr Kolb's meter as well as Ahlstrom's Gas Station 100 and Mütek's gas measuring meters. Dr Kolb's device is based on compression and it measures only entrained gas, while the other two also measure dissolved gas.

3.3. Stabilisation of gas bubbles

Gas bubbles are unstable and they can be stabilised by surface-active dissolved and colloidal substances in the fibre suspension. Unstabilised small gas bubbles dissolve quickly by diffusion, unless the liquid is already oversaturated with dissolved gas, in which case the bubbles will grow by bubble coalition. Large gas bubbles will rise out of the fibre suspension, if the suspension consistency is not too high. The gas bubbles are called stabilised, if they remain for an appreciable length of time. In papermaking this is from tens of seconds to hours /22/. Pietikäinen has measured a diameter from 60 to 100 μm for stabilised air bubbles /23/.

There are several methods for the gas bubbles to stabilise. The main stabilising mechanisms are /24/:

- capillary pressure stabilisation
- particle stabilisation
- Marangoni effect (surface tension gradients)
- electrostatic stabilisation of the lamella
- high viscosity of the bulk liquid
- high surface viscosity of the lamella

Capillary pressure stabilisation arises because the pressure is different in different parts of a distorted lamella. The liquid pressure at a convex surface is higher than at a concave liquid surface. Because of the pressure difference, liquid flows from thick points of the lamella to the thin points of lamella /24/.

Particle stabilisation is obtained if the particles have a suitable balance between hydrophobic and hydrophilic properties. Maximum stabilisation is obtained if the surface of the particles has the same attraction to both water and air; i.e. the contact angle between the aqueous solution and particle is 90° /24/.

If a bubble lamella is elastic, it can be deformed by external forces without breaking the lamella – it resumes its original shape when the force is withdrawn. In the Marangoni effect, when the lamella of a surfactant-stabilised bubble is stretched, the surface tension increases because the number of surface-active molecules decreases in the stretched region. The lamella has thus rendered elasticity. Surface-active molecules from surrounding regions are drawn towards the region with higher surface tension. If the surfactant concentration is small, the surface tension is high and the changes in surface tension during stretching are small. The elasticity is reduced and the solution shows a low tendency for the gas bubbles to stabilise /24/.

Electrostatic stabilisation can occur if the lamella has been drained of water to such a degree that the thickness of the electrostatic double layer is of the same magnitude as half the lamella thickness. The repulsion between the double layers prevents further drainage of liquid from the lamella /24/.

Protein solutions show a high surface viscosity stabilisation of bubbles close to the iso-electric point, partly because the protein molecules do not repel each other, which results in good cohesion at the interface. The cohesion causes the interface to become relatively immobile, so a high surface viscosity is obtained /24/ .

3.4. Effects of pressure and temperature on gas content

Pressure and temperature affect the volume of air and gas. Furthermore, gases in the air can dissolve as individual molecules into the water of the fibre suspension. An increase in pressure will reduce the volume of gas bubbles and increase the dissolving capacity of water. An increase in water temperature will reduce the gas dissolving capacity, and dissolved gas molecules will be precipitated into gas bubbles. Boyle’s ideal gas law, Equation 1, applies quite well for the air volume in the fibre suspension. Henry’s law, Equation 3, can be used to calculate the dissolution of gas into water.

$P_i = H_i x_I$ (3)

where P_i is the partial pressure of the i:th gas, H_i is Henry's constant, which is temperature-dependent and x_i is the mole fraction of the gas in the liquid.

The dissolution of gas increases linearly with increasing pressure, Figure 3.1. The graph has been calculated using Equation 3. The value for $H(O_2)$ at 50 °C is 0.000000423 and at 27 °C 0.000000336 and the value for $H(N_2)$ at 50 °C is 0.000000837 and at 27 °C 0.000000675. The dissolution decreases when the temperature increases, Figure 3.1. Henry's law is valid when the concentrations and gas partial pressures are relatively low.

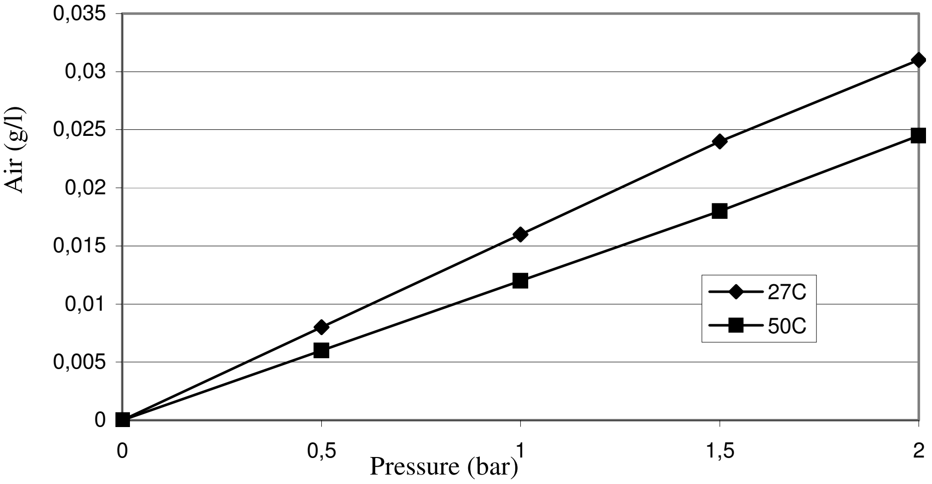

Figure 3.1. Dissolution of air into water as a function of pressure.

If the pressure is decreased or temperature is increased, the dissolved gas will precipitate into gas bubbles. The precipitated bubbles from dissolved gas can be produced by either homogeneous or heterogeneous nucleation /36/. In homogeneous nucleation the bubbles form within the bulk of the liquid phase, and in heterogeneous nucleation the bubbles form at a solid-liquid interface. Homogeneous nucleation only occurs under conditions of large superheats or high supersaturation levels /39,25/. In precipitation the average diameter of the forming bubbles is between 30 and 120 µm /26/.

3.5. Effects of chemistry on gas content

Gas bubble stabilisation is affected by fibre suspension pH, Z-potential, conductivity and surface energy. The Z-potential, conductivity and surface energy affect the adhesion between particles and gas bubbles /27/. The conductivity also reflects the amount of some of the dissolved material. If the dissolved material is surface-active, the surface energy will decrease. Lower surface energy improves the foam building tendency /24/.

If the pH is raised, the amount of dissolved material from the wood is increased, especially with mechanical pulps /28/. Furthermore, the solubility of calcium carbonate pigment is affected by pH and attains an equilibrium with the surrounding aqueous medium. The equation can be presented with the following Equation 4.

$CaCO_3 \Leftrightarrow Ca^{2+} + CO_3^{2-}$ (4.1)
$H_3O^+ + CO_3^{2-} \Leftrightarrow HCO_3^- + H_2O$ (4.2)
$HCO_3^- + H_3O^+ + \Leftrightarrow H2CO_3 + H_2O$ (4.3)
$H_2CO_3 \Leftrightarrow CO_2 + H_2O$ (4.4)
$CO_2 + H_2O \Leftrightarrow CO_2 \uparrow + H_2O$ (4.5)

When pH is below 5, the equilibrium is at CO_2 (gas) and H_2O, Equation 4.5. In a pH close to 8, the dissolution becomes very small and the equilibrium is at $CaCO_3$, Equation 4.1.

3.6. Effects of raw materials on gas content

The stock composition has a major influence on gas entrainment. The fibre raw material, chemical additives, pigments and interfering substances (pulping and bleaching residuals, ions in fresh water as well as additives from broke) together determine the stability of gas bubbles in a papermaking furnish.

3.6.1. Fibre raw materials

Stock preparation, beating, bleaching and washing, influences the gas amount by affecting the amount of dissolved and colloidal material released from wood. Pitch and lignin have been found to stabilise gas bubbles. Beating increases the amount of extractives (pitch) and lignin in stock. Furthermore, the increased amount of fine material and broken fibres will increase gas entrainment by providing additional surfaces for bubble attachment /22,23/.

Different pulps contain different amounts of fines as well as dissolved and colloidal substances, which affects gas entrainment. Mechanical pulps retain more of their extractives and lignin than chemical pulps, because mechanical pulps are usually not washed. Similarly, well-washed and bleached pulps do not take up as much gas as unwashed, unbleached pulps, because their lignin and pitch contents are lower. The washing of pulp in particular reduces the quantity of substances which stabilise gas. Recycled pulp has been reported to contain high amounts of gas due to the large amount of surface-active dissolved and colloidal material from wood material, printing and deinking chemicals, if deinked /22,23/.

3.6.2. Pigments and papermaking chemicals

Several additives are used in papermaking and many of them are surface-active. Pietikäinen has studied the effects of various chemicals and pigments on the stabilisation of gas bubbles. According to his studies, fresh rosin size, non-ionic surfactant as well as cationic and anionic retention aids were all effective in stabilising entrained air. Lignin and extractives released during mechanical pulping were also found to act as strong stabilisers of entrained air. Calcium carbonate, clay, titanium dioxide and talc fillers all had minor effects on the stabilisation of air bubbles in the slurries tested /23/.

3.7. Formation of gas bubbles

The formation and expansion of a gas bubble increase the surface area of the bubble and this requires work, Equation 5.

$$\Delta W = \sigma \Delta A, \qquad (5)$$

where ΔW is the required work for the new surface area, σ is the surface energy of the liquid and ΔA the increased surface area of the gas bubble. Lower surface energy of the liquid decreases the energy needed for the formation of gas bubbles and foam.

The formation, i.e. precipitation, of a gas bubble is quite slow if the pressure drop is small. High turbulence or a great pressure drop can increase the precipitation significantly into a few seconds /29,30/. In practices, the gas bubbles can precipitate quickly in mill papermaking conditions, where the pressure drops can be high, for example before the pumps and after the headbox slice.

3.8. Dissolution of gas bubbles

The gas is dissolved from the bubble into the liquid when the gas pressure inside the bubble is higher than the pressure of gas in the liquid and the pressure from the gas dissolved into liquid is less than the hydrostatic pressure. The compressive forces acting on a bubble are surface tension and hydrostatic pressure. The resisting force is the pressure inside the gas bubble. The forces in the bubble film are electrical and steric. The difference in pressure across the bubble surface is given by Laplace's equation.

$$p_b - p_n = 2\sigma / r, \qquad (6)$$

where p_b is internal pressure of a gas bubble, p_n is the hydrostatic pressure in liquid, σ is the surface tension of liquid and r is the radius of the gas bubble.

The pressure inside the gas bubble increases with decreasing bubble radius. When the liquid is saturated or undersaturated with gas, the pressure of the dissolved gas is less than the hydrostatic pressure. This means that the gas pressure inside the bubble is higher than the gas pressure in the liquid and gas will diffuse out of the bubble. The small gas bubbles dissolve quicker than the large gas bubbles in the liquid. The dissolution time for a bubble with 10 µm diameter is about 6 seconds and for a diameter of 100 µm about 600 seconds, when the water is saturated with gas and the temperature is 300 K /23/. In a simple two-phase system, with pure liquid and a limited number of gaseous components, it is possible to calculate the phase transitions. However, in papermaking conditions with a complex three-phase system with solid material the calculations become very difficult.

The solubility of gases in liquids is based on the intermolecular forces between gas and liquid molecules. The electron cloud of non-polar gases such as O_2 and N_2 is normally symmetrically distributed between the two atoms. When a polar water molecule approaches a non-polar molecule, the electron cloud retreats and reduces the repulsion of the negative forces. The gas molecule forms a temporarily induced dipole, causing the gas molecule and H_2O to become electrically attracted to each other. This attraction between the oppositely charged poles is a dipole-induced dipole force, often referred to as the Van der Waals force. The creation of these forces explains the mechanism by which gases dissolve in water. As these forces become stronger with increasing molecular size, this mechanism also explains the greater solubility of gases of larger molecular size /21/.

3.9. Foam

Foam is formed from stabilised gas bubbles that have risen to the surface of the liquid. In clean water the gas bubbles do not create foam /31/. Foam formation requires dissolved or colloidal surface-active substances that create a film around the gas bubble and stabilise it.

For the foam to be preserved after its formation, it has to be stable. Gravitation and capillary forces cause the foam film to collapse, unless it is stabilised. Foam is only stabilised if the contact angle between the films connecting the gas bubbles is 120°. Stabilising mechanisms are described in Chapter 3.3. /24/.

3.10. Flotation

In flotation, particles are attached to gas bubbles, rising out of the water if their weight is less than the weight of the water that they replace. In flotation there are three basic events, Figure 3.2.

1. Collision of particle and bubble. The probability P_c of the collision is affected by the amount of gas bubbles n_k, number of particles n_p and other circumstances z_c, such as hydrodynamics and diffusion.

2. Attachment of particle and bubble. This is affected by the probability P_b that the repulsive forces between the bubble and particle are small enough for the adhesion. Furthermore, there is the probability P_k that the thin liquid film between the particle and bubble will break quickly.

3. Rising of the agglomerate. The probability P_s that the agglomerate will withstand the shear forces in the liquid and rise to the surface of the liquid.

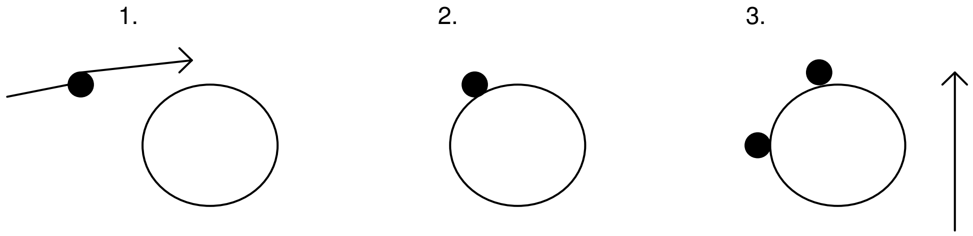

Figure 3.2. Three basic events in flotation: 1. Collision of particle and bubble, 2. Attachment of particle and bubble, 3. Rising of the agglomerate /32/.

The velocity of the particles removed from the liquid with flotation can be calculated with Equation 7.

$$dn_p / dt = P_c\, P_b\, P_k\, P_s = n_k,\ n_p\, z_c,\ P_b\, P_k\, P_s \qquad (7)$$

The adhesion strength, i.e. flotation strength of air bubbles on fibres, can be calculated with the following equation:

$$F_a = \pi \cdot d_i \cdot \sigma \cdot \sin \alpha, \qquad (8)$$

where F_a is the adhesion strength of gas bubbles on particles, d_i is the diameter of the contact surface between the gas bubble and particle, σ is the surface tension of the liquid phase and α is the contact angle between gas bubble and particle /33/.

In laboratory trials conducted by Isler (1978) air bubbles with a diameter smaller than 100 μm were found to adhere to fibres /41/. If the particles are too large for the size of the bubble, the high turbulence will dislodge the particle from the surface of the bubble. If the particle is too small, the surface tension and electrostatic double layer forces will prevent the particle from adhering to the surface of the bubble /34,35/.

4. GAS REMOVAL FROM A PAPERMAKING FIBRE SUSPENSION

Gas removal is used to avoid detrimental effects of air and other gases on paper properties and papermaking processes /36,37,38/. There are two possible mechanisms which cause gas bubbles to be retained in the fibre suspension: 1. Mechanical entrapment of bubbles in the fibre network and 2. Adhesion of bubbles to fibres. For adhesion to occur, the fibres must have hydrophobic regions on the surfaces or gas pockets trapped in surface cavities to allow the bubbles to grow /39/. Some authors have postulated that gas bubbles adhere to fibres: Gavelin, Isler and Karras et al. /40,41,42/. In spite of much discussion in the literature, there is no published photographic evidence of bubbles attached to fibres in a production-scale pulp- or papermaking process /43/. Therefore, Ajersch and Pelton assume, based on to their experiments, that air bubble-pulp fibre adhesion rarely occurs /44/.

Gas can be removed either chemically or mechanically. Good process design, including pipeline design and stock composition, and the right temperature, pH and pressure will prevent air entrainment in the fibre suspension /16,45/. Although this reduces the need for gas removal, some mechanical removal of gas is still required. Some free gas is removed in the wire pit, but for better air removal vacuum or centrifugal deaeration is generally used.

4.1. Gravitational gas removal

Free gas is removed in the wire pit with gravitational force. The wire pit must be large enough to provide sufficient time for the bubbles to rise to the surface. The terminal velocity at which a small bubble rises can be approximated with Stokes equation:

$$v = \frac{g \cdot \left(\rho_p - \rho_f\right) \cdot \phi^2}{18\mu}, \qquad (9)$$

where v is the velocity of the particle, g is acceleration due to gravity, ρ_p is particle density, ρ_f is fluid density, ϕ is particle diameter and μ is the viscosity of the liquid.

Stokes equation is valid for small solid spherical particles, and presumes a no-slip condition at the particle surface. Bubbles enforce a more relaxed boundary condition, and in fact have about 50 % higher terminal velocity. In practice, is has been found that the velocity of fall of the white water in the wire pit has to be below 0.15 m/s to give enough time for the gas bubbles to rise in the wire pit /8/. If the velocity of white water is too high, the gas bubbles will not have enough time to rise, and if it is too low, there will be an increase in slime build-up on the walls.

4.2. Vacuum gas removal

In a vacuum deaerator gas is removed by spraying the fibre suspension into a vacuum chamber, Figure 4.1. The suspension impinges on the chamber walls, which increases the removal of gas from the fibres. The boiling caused by the vacuum and the physical impact removes the entrained and dissolved gas from the fibre suspension, provided the vacuum deaerator is correctly adjusted /46/.

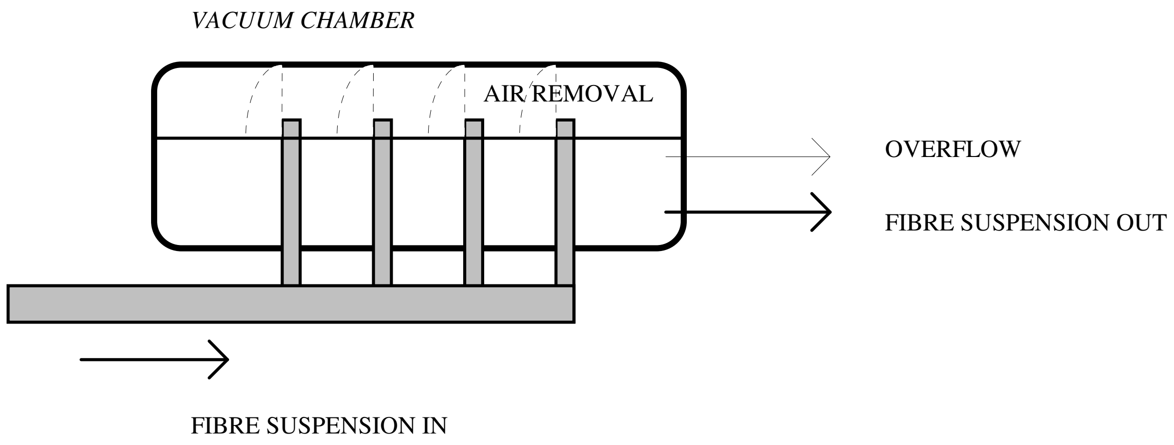

Figure 4.1. Vacuum deaerator for air and gas removal from fibre suspensions.

4.3. Chemical gas removal

Very often, mechanical gas removal is not effective enough and chemical gas removal is used to further decrease the gas amount. Chemical deaerators (defoamers, antifoamers) function by three main mechanisms:

1. Hydrophobic particles break up the stabilising surface film on the air bubbles.
2. A non-stabilising chemical replaces the stabilising agents on the bubble wall, leading to collapse of the bubbles.
3. Low surface tension defoamers spread on the surface of the fibre suspension and break up the foam.

Generally, defoamers function via more than one of these mechanisms. Defoamers usually consist of hydrophobic particles, surface agents, spreading agents and emulsifiers with oil and/or water as a carrier. With chemical deaerators an overdose must be avoided because this might cause deposits on the paper machine /47/. /22,48/.

4.4. Centrifugal gas removal

The “pomp” centrifugal pump developed and invented by Mr Paul Meinander for air and gas removal from fibre suspensions is intended to replace both the wire pit and the vacuum deaerator /49/.

In the pomp, the gas is centrifuged out of a ring of fibre suspension, Figure 4.2. From the separation zone, the degassed fibre suspension flows to the pumping chamber and is removed by pumping. Besides removing entrained air, the pomp reduces the amount of white water in the short circulation, which should speed up the dynamics of the process. /7,49/.

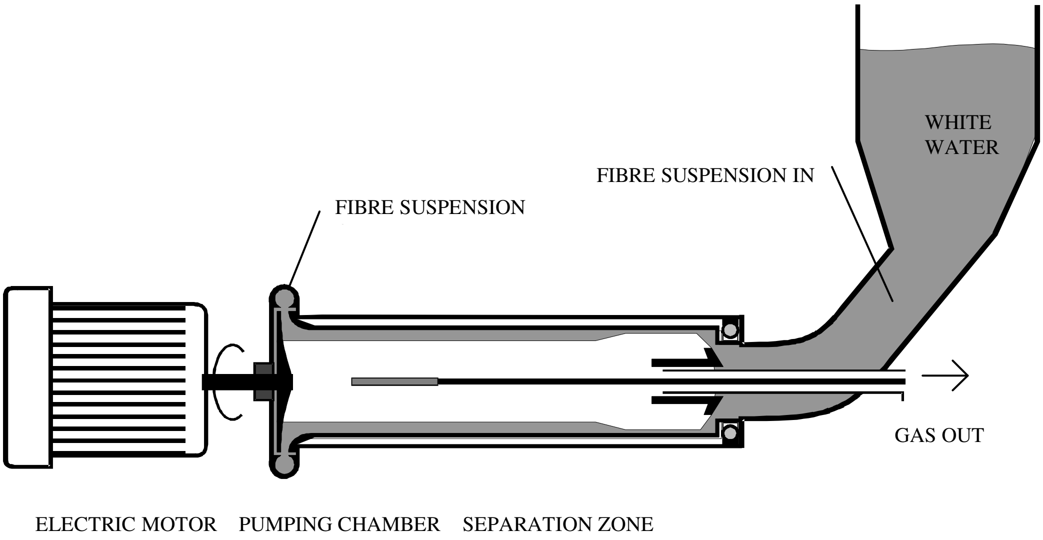

Figure 4.2. Pomp centrifugal pump for air and gas removal from fibre suspensions.

Stokes equation is used to calculate the particle removal efficiency of a centrifuge /50/. Based on the assumption that gas bubbles behave in the opposite way to heavy particles removed in a centrifuge, the diameter of the gas bubbles removed in the pomp can be calculated from equation 10, which is derived from equation 9.

$$\phi_b = \left[\frac{d/(V/f) \cdot 18\,\mu}{a_p \cdot (\rho_b - \rho_f)} \right]^{1/2}, \qquad (10)$$

where ϕ_b is bubble diameter, d is distance travelled by the bubble, V is the volume of the water layer inside the pomp, f is the flow rate through the pomp, μ is the viscosity of water, a_p is the acceleration force inside the pomp, ρ_b is bubble density and ρ_f is water density.

According to equation 10, the minimum diameter of the bubbles being removed is 19 μm (assuming that the pomp exerts an acceleration force of 100 g, the distance travelled by the bubble is 0.02 m, the volume of the water layer inside the pomp is 60 l, the flow through the pomp is 60 l/s, the viscosity of water is $1040 \cdot 10^{-6}$ Ns/m^2 and ρ_b-ρ_f is 990 kg/m^3). If needed, the gas removal efficiency can be easily improved by increasing the length of the separation zone or the acceleration force.

5. FIBRE RECOVERY WITH FLOTATION

The purpose of the paper machine's fibre recovery system is to recover as much as possible of fibres, fines and pigment materials from the white water for the reuse in papermaking. Filtration, sedimentation and microflotation are the most common methods used. The fibre recovery system is usually connected to the process so that 1) all the overflow water from the wire pit is cleaned, or 2) only the shower waters and the waters leaving the process are cleaned. The latter method requires less fibre recovery capacity, but quality variations in the white water are greater than in the first option.

Filtration is done with a drum or a disc filter. The latter has a higher capacity. In filtration the white water is divided into recovered material, cloudy filtrate and clear filtrate. In some disc filters there is even an ultra-clear filtrate. The approximate dry solids in different fractions are: recovered material 30-50 g/l, cloudy filtrate 400 mg/l, clear filtrate 50 mg/l and ultra-clear filtrate 5 mg/l /51/. Sedimentation is based on gravitation and requires a large tank with enough volume for the recovered material to settle at the bottom of the tank. Sedimentation is rarely used on larger paper machines.

Flotation technology is used in the paper industry for deinking recycled paper, for recovering fibres from paper machine white waters and for clarifying wastewater. During flotation the particles adhere to air bubbles and are removed from the suspension. Flotation is often divided into microflotation and normal flotation. The latter is used in deinking as well as in mineral separation in the mining industry, with the bubble size being larger than in microflotation. Microflotation is used in fibre recovery and in wastewater clarification.

In microflotation all the particles are removed from the suspension, while in deinking only the hydrophobic ink particles are removed. Microbubbles can be generated by several methods: electrochemically, by injection of gas through porous devices and by reducing the pressure of a liquid, which has been saturated with air at high pressure /52/. The latter method is usually called dissolved air flotation (DAF).

In DAF the microbubbles are produced by reducing the pressure of water, which has been saturated with air at high pressure (4-6 bar). When the pressure is reduced, air bubbles with a diameter from 30 to 120 µm /26/, are formed. These bubbles are attached to the material in the white water. The air bubble agglomerates rise and the fibres, fines and pigments can be collected. The clear fraction is taken close to the bottom. Heavy substances unaffected by flotation are collected at the bottom /26/.

In fibre recovery with flotation the clear fraction has a dry solids content below 50 g/l. However, the dry solids content of the material recovered through flotation is clearly lower than that of material recovered with filtration /7/. Microflotation and sedimentation are quite slow when compared to filtration /7,26/.

6. EXPERIMENTAL

In the experimental part, the effect of centrifugal force on gas bubbles and the flotation process was studied at laboratory scale. The target was to examine the effect of centrifugal force on flotation fibre recovery (hypothesis 1 in the thesis) and on centrifugal gas removal (hypothesis 2 in the thesis). Removal of entrained gas with centrifugal force was also studied in two commercial paper mills.

The effect of entrained gas on papermaking was studied in a pilot mill trial. In addition, a trial was conducted with a Moving Belt Drainage Tester (MBDT) to find out if precipitated gas bubbles behave differently from dispersed gas bubbles, which were used in the pilot mill trial. Most studies reported in the literature have been made with dispersed gas bubbles /1,14,48/. The objective was to characterise the effect of gas on papermaking (hypothesis 3 in the thesis).

6.1. Effect of centrifugal force on flotation

The use of centrifugal force to promote flotation fibre recovery was examined in the laboratory with equipment specially developed for these trials. The possibility of removing entrained gas by means of centrifugal force was also studied. Three microflotation trials were made: The first one to study the effect of centrifugal force on microflotation (injection of gas through a porous device); the second to study the effectiveness of dissolved air flotation, i.e. DAF, without centrifugal force; and the third to examine the effect of centrifugal force on DAF (Paper I).

The samples were white water from two commercial paper machines producing release paper and lightweight coated paper (LWC). Commercial paper machine white waters were used in order to cover all the compounds present in normal papermaking . It is well known that mechanical pulps used for LWC effectively stabilise gas bubbles /22,23/. A release paper stock with no mechanical pulp used was chosen for comparison.

The release paper stock consisted of chemical pulp (a mixture of birch and pine), starch, defoamer, alum, rosin size, cationic PAM and some clay and latex from coated broke. The pH was 4.0, the concentration of suspended solids in the wire pit water 300 mg/l and the ash content 10 mg/l. Microflotation (DAF) is used at the mill in question for fibre recovery.

The LWC paper stock consisted of chemical and groundwood pulp, starch, PEI, alum, defoamer and some kaolin and latex from coated broke. The pH was 4.6. The concentration of suspended solids in the wire pit water was 3400 mg/l and the ash content 1360 mg/l. A disc filter is used at the mill in question for fibre recovery.

6.1.1. Centrifugal force and microflotation

The effect of centrifugal force on microflotation (injection of air through a porous wall) was studied. The sample was mixed in a blending vessel and pumped from there to a flotation vessel, where it formed a ring due to the centrifugal force. The centrifugal force was caused by horizontal rotation of the flotation vessel. Air was blown through the water ring from the outer wall of the flotation vessel, which was made of a porous sinter metal (Paper I).

If flotation occurs, the suspended solids and ash contents should decrease. There was no flotation in practice, Figure 6.1. The air bubbles did not distinctly adhere to the fibres or fillers, and the airflow through the water layer had no effect.

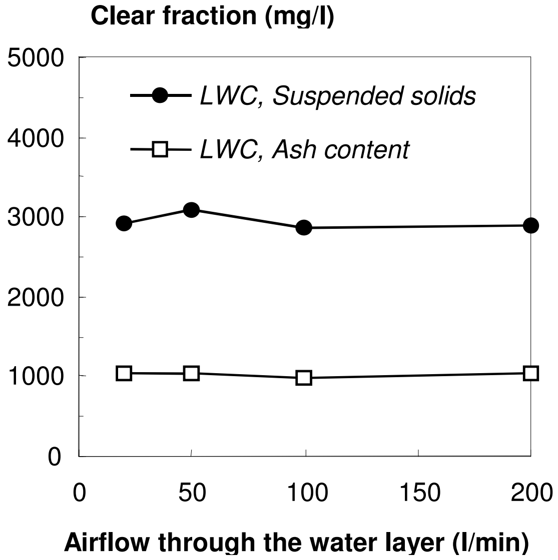

Figure 6.1. Suspended solids and ash contents of the clear fraction as a function of airflow through the water layer with injection of air through a porous wall. The retention time of the sample was 60 seconds and the centrifugal force 10 g.

Besides different air flows through the water layer, also different centrifugal forces were tested. No clear flotations were found in any of these trials with the injection of air into the fibre suspension through a porous wall.

In laboratory trials conducted by Isler and Widmer (1978) air bubbles with a diameter smaller than 100 µm were found to adhere to the fibres /9/. The bubble size through the porous wall should have been right for at least some flotation of the air bubbles to the particles, so the entrained (dispersed) air bubbles can be assumed not to adhere distinctly to the fibres and fillers in papermaking process conditions. The findings of this trial are confirmed by the research by Pelton and Piette and Ajersch and Pelton /43,36/ (Paper I).

6.1.2. Centrifugal force and dissolved air flotation

First, dissolved air flotation (DAF) without centrifugal force was studied. From the pressure and blending vessel, at a pressure of 3 bar, the sample was transferred by the pressure difference to the flotation vessel, where the dissolved air was released to normal pressure. During flotation the sample was divided into two streams: a clear fraction and a suspended solids fraction (Paper I).

The effect of flotation time on dissolved air flotation is illustrated in Figure 6.2. The suspended solids and ash contents decreased with an increase in the flotation time. To ensure effective flotation, the flotation air mixing time must be long enough; in these trials it was found to be at least 30 seconds (Paper I).

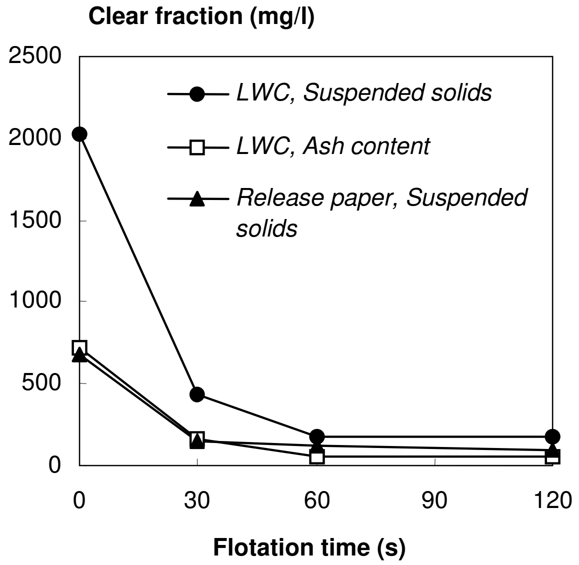

Figure 6.2. Effectiveness of flotation in dissolved air flotation (DAF) as a function of flotation time. The dissolution pressure was 3 bar.

In the studies by Pelton and Piette and Ajersch and Pelton, the gas bubbles did not nucleate on wetted fibres, which was observed in the DAF trials, where both the fibres and fillers were flotated /43,36/. In these DAF trials, the pressure difference was relatively high, with the pressure dropping quickly from 3 bar overpressure to normal pressure, and the whole samples were well mixed with air in the blending vessel for a few minutes, in contrast to the trials conducted by Ajersch and Pelton /36/. In their experiments, the pressure difference and mixing of gas were presumably less and the whole samples were not subjected to pressure changes. It can be assumed that for air or gas bubbles to nucleate on the surface of wetted fibres, a sufficient pressure difference is needed, and that the fibres should have hydrophobic regions or gas pockets on the surfaces for the air bubbles to nucleate /39/. However, it is also possible that the fibres were mechanically entrained by the air bubbles in the DAF trials, and not by adhesion. Nevertheless, it is more likely that the air bubbles stick to the fibres because of the adhesion caused by the heterogeneous nucleation in the trials. Similar results have been obtained by Stoor et al. /21,53/.

A pressure difference, such as the one used in DAF trials, may also occur on a commercial paper machine, so flotation of fibres and fillers is possible in normal papermaking conditions.

The effect of centrifugal force on DAF was studied. The sample from the pressure and blending vessel, at a pressure of 3 bar, was transferred by the pressure difference to the horizontally rotating flotation vessel, where the dissolved air was released into bubbles at normal pressure. In the flotation vessel, the sample formed a ring due to the centrifugal force caused by the horizontal rotation of the flotation vessel. During flotation, the sample was divided into two streams: a clear fraction and a suspended solids fraction (Paper I).

The effect of centrifugal force on DAF and the flotation of air bubbles to fibres is illustrated in Figure 6.3. The centrifugal force did not significantly improve the flotation in the trial. Air bubbles were released from the particles when the centrifugal force increased. The shear forces between particles and bubbles increased as the centrifugal force was raised, which probably caused the bubbles to disengage from the particles before the maximum centrifugal force was reached (Paper I).

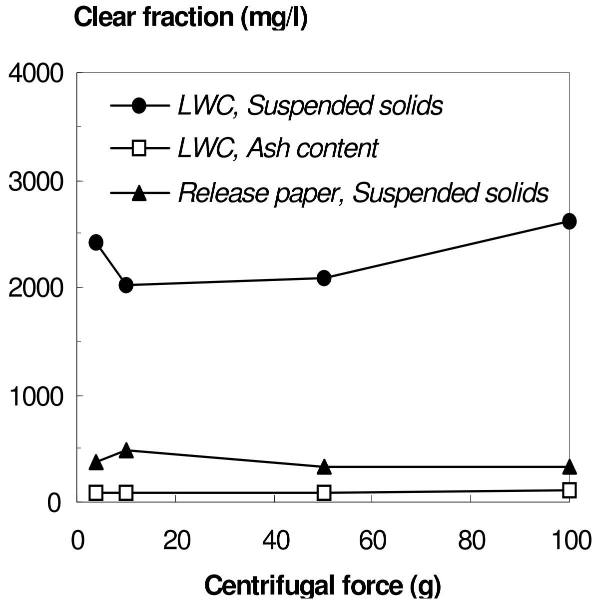

Figure 6.3. Suspended solids and ash contents of the clear fraction as a function of centrifugal force in dissolved air flotation (DAF). The retention time of the sample was 40 seconds and the dissolution pressure 3 bar.

6.2. Removal of gas with centrifugal force

The objective was to examine the gas removal capacity of centrifugal force in mill trials on two commercial paper machines. The "pomp" centrifugal pump was installed on paper machines producing release paper and lightweight coated (LWC) paper (Papers II and III).

The pomp was installed on an additional line leading from the wire pit and returning to the wire pit. The air content was measured before and after the pomp. Air contents were measured using the expansion and compression methods. The expansion method can be used to determine both entrained and total air, which also includes dissolved air. The compression method, which measures only entrained air, was used when the consistency of suspended solids in the fibre suspension was above 1.5%. The expansion method equipment functioned at suspended solids contents below 1.5 % /1,18/.

The release paper stock consisted of chemical pulp (a mixture of aspen, birch and pine), starch, alum, rosin size, cationic PAM and some clay and latex from coated broke. The pH was below 5, the concentration of suspended solids in the wire pit water 0.3 g/l and the ash content less than 8%. The mill uses the wire pit and a deaerator to remove gas from the wet-end process (Paper II).

The LWC paper stock consisted of chemical and groundwood pulp, starch, PEI, alum, defoamer and some kaolin and latex from coated broke. The pH was 6.9. The concentration of suspended solids in the wire pit water was 5.8 g/l and the ash content 11%. The mill uses the wire pit, a vacuum deaerator and a chemical deaerator to remove gas from the wet-end process (Paper III).

In the release paper machine mill trial, the entrained air content ahead of the pomp varied between 0.3 and 1.3% and the total air between 0.3 and 1.6%. The large variation in air content ahead of the pomp was due partly to turbulence caused by the extra pipeline from the wire pit to the pomp. After the pomp, the entrained air content was below 0.1%, Figure 6.4. (Paper II).

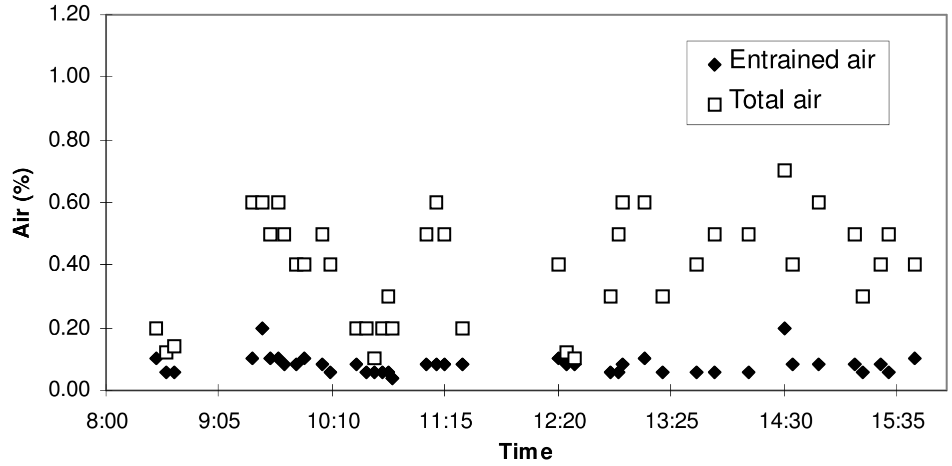

Figure 6.4. Air content after the pomp in release paper machine trial. The two peaks for the content of entrained air were caused by test adjustment of the pomp.

The air contents in the LWC paper machine mill trial after the pomp are shown in Figure 6.5. The entrained air content decreased from an average of 0.46% ahead of the pomp to an average of 0.08% after the pomp (Paper III).

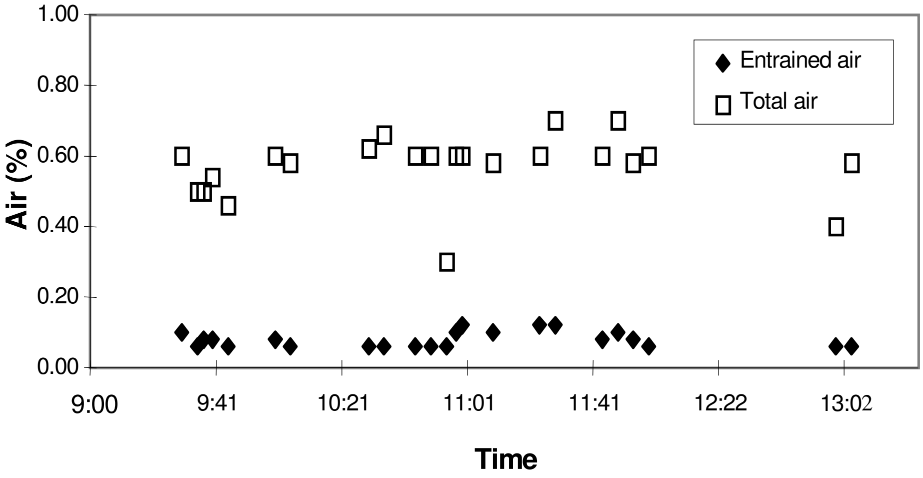

Figure 6.5. Air content after the pomp in the LWC paper machine trial.

The pomp thus removed almost all the entrained air from the wire water. The amount of dissolved air was not greatly affected by the pomp. However, the entrained air removal achieved with the pomp was similar to that achieved with vacuum deaerators /7,14/ (Paper III).

The pomp's air removal efficiency depends on the centrifugal force: the higher the centrifugal force, the smaller the bubbles that are removed, Equation 10. The time during which the bubbles are subjected to centrifugal force is also critical. The average residence time is found by dividing the fluid volume inside the pomp with the volumetric flow rate. The pomp's entrained air removal efficiency during the mill trials was found to be at least as high as the estimated the air bubble removal efficiency according to Equation 10 in Chapter 4.4. /7/ (Paper II).

The pomp can remove dissolved air, if turbulence or vacuum is used. Turbulence can convert the dissolved air quickly into entrained air, which can then be removed with a pomp /29/. If vacuum is used inside the pomp, the pomp will remove practically all the entrained air at that pressure. When the white water returns to atmospheric pressure, some of the dissolved air has been removed. Vacuum has been used with good success in pomp mill installations /54 /.

6.3. Effect of entrained gas on papermaking

The study was carried out on KCL's pilot paper machine to study quantitatively the effects of entrained gas on papermaking. The pilot paper machine has a Fourdriner wire section and the headbox stock and white water originated from two different commercial paper machines: a fine paper machine and a machine producing machine finished coated (MFC) paper (Paper IV).

In the pilot paper machine trials the process conditions were kept constant as far as possible. The stocks used in the trials consisted of chemical and mechanical pulps. The fine paper stock consisted of pine chemical pulp, special pulp (aspen mechanical pulp), calcium carbonate pigments, starch, deaerator, fixative, talc, retention aid, bentonite and alum, as well as calcium carbonate and latex from coated broke. The pH was 7.3. The mill uses the wire pit and a vacuum deaerator and chemical deaerator to remove gas from the wet-end process.

The MFC paper stock consisted of pine chemical pulp and spruce thermomechanical pulp (TMP), calcium carbonate pigments, fixative, PAM, bentonite, alum, deaerator and some calcium carbonate, clay and latex from coated broke. The pH was 7.5. The mill uses the wire pit and a vacuum deaerator and chemical deaerator to remove gas from the wet-end process.

The only variables used were grammage and entrained air content. Air was injected into the short circulation after the fan pump and it was dispersed with a static mixer in the pipeline. The air content was measured with Ahlstrom's on-line gas content meter and all on-line measurement data and laboratory data from the trials were collected by the WEDGE process analysis system. For practical reasons, complete deaeration was not effected for the reference points with zero air content, and these points therefore contain small amounts of entrained air (below 0.1 %). The grammages for the different papers were typical base paper grammages used at the mills supplying the stocks. Table 6.1 shows the trial conditions. The following properties were measured from the pilot mill trial: water line, vacuum in suction boxes, tensile and tear strength, porosity, roughness, initial wet strength, formation, grammage and ash content as well as the number of spots and pinholes./55/ (Paper IV)

Table 6.1 Paper machine settings in pilot paper machine trials.

Properties	*Fine paper*	*MFC paper*
Grammage (g/m^2)	40 and 70	40 and 60
Speed (m/min)	80	80
Production (kg/h)	15 - 25	15 – 22
Temperature (ºC)	45	45
pH	>7	>7
Target entrained air content (%)	0 - 0.6	0 - 0.6

Online formation was measured with AFORA Microform, which is based in the variation of light transmission. Laboratory formation was measured with Ambertech, which is based in the beta radiation absorption. Both methods are described in details in their manuals. The pilot trial results permit no clear conclusions to be made on the effect of gas to the formation. (Paper IV)

The drainage rate of the MFC paper stock was much lower than that of the fine paper, probably due to the larger amount of fines (smaller Canadian Standard Freeness value). No significant difference was found in the effect of entrained air between fine paper and MFC paper in the pilot paper machine trials Figure 6.6. Normally, it is difficult to disperse air in a fine paper stock, but in this case the fine paper stock also contained mechanical pulp. Dissolved and colloidal substances from the mechanical pulp stabilise air bubbles and thus retard the removal of entrained air from the stock (Paper IV).

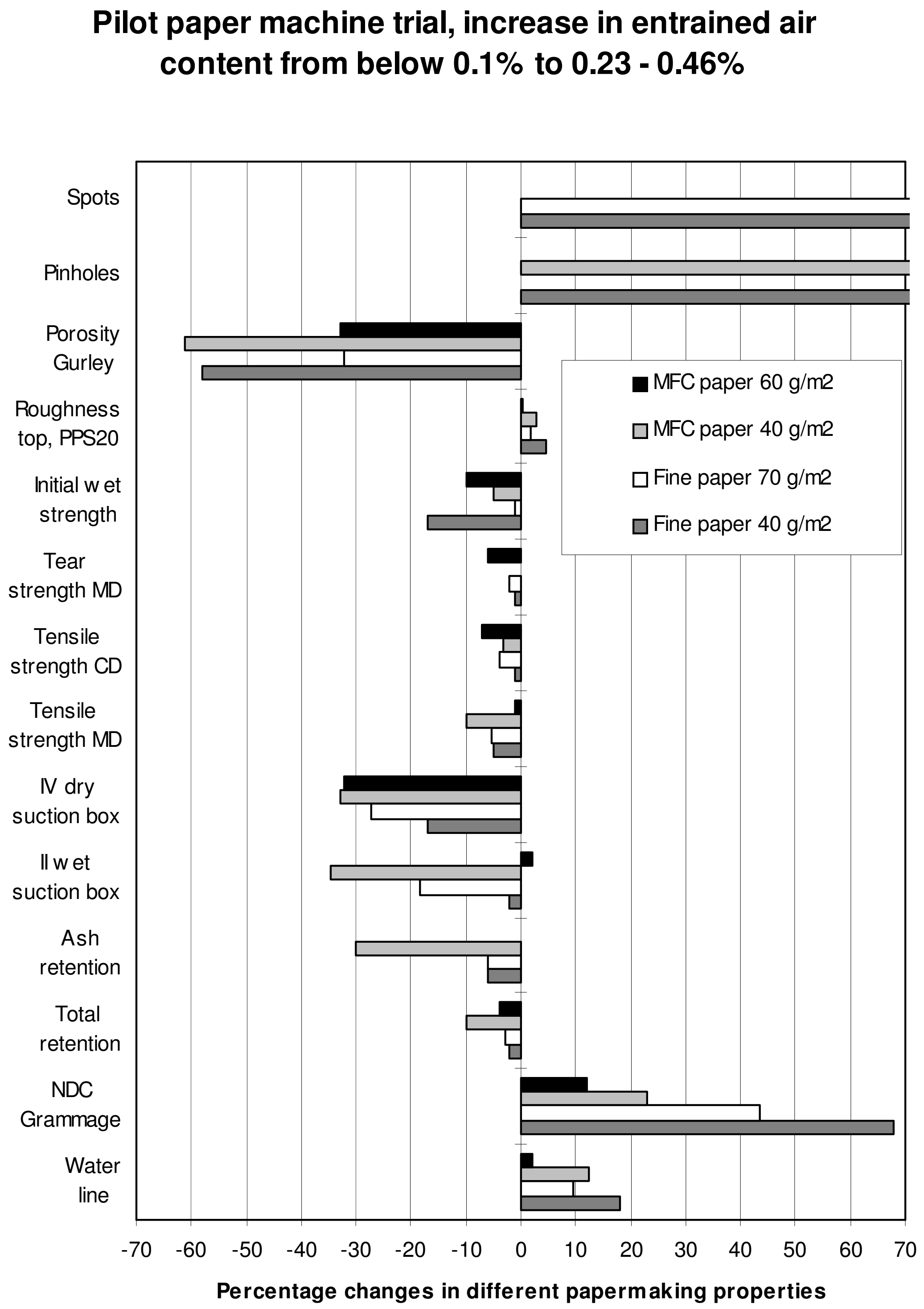

Figure 6.6. Percentage changes in papermaking properties in pilot mill trials as the entrained air content of the stock increased as follows: fine paper 40 g/m^2 from 0.09 to 0.31%, fine paper 70 g/m^2 from 0.05 to 0.37%, MFC paper 40 g/m^2 from 0.02 to 0.23% and MFC paper 60 g/m^2 from 0.05 to 0.46%.

In the pilot paper machine trials, the drainage, vacuum levels in the dry suction boxes, porosity and spots were distinctly affected by the entrained air content, Figure 6.6 (Paper IV). In addition to the above-mentioned effects, the tensile indices and the number of pinholes were affected at low grammage. These effects were not as obvious at high grammage.

The impaired drainage was well seen with the removal of the water line. The wire section of the pilot paper machine is in figure 6.7. With fine paper stock the water line was approximately at 130 cm and with MFC stock the water line was approximately at 340 cm, before the addition of air. With fine paper stock the water line moved 23 cm with 40 g/m2 and 13 cm with 70 g/m2 after the addition of air. With MFC paper stock the water line moved 41 cm with 40 g/m2 and 14 cm with 60 g/m2 after the addition of air. The place of the water line was visually observed by the pilot paper machine operator.

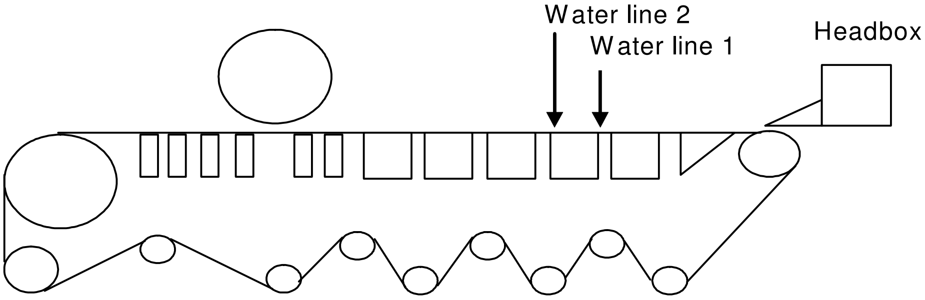

Figure 6.7. Pilot paper machine wire section. The total length of the wire section is 8,1 meters. Water line 1 is the location of the water line before the addition of air and water line 2 after the addition of air.

The effect of retention aid decreased somewhat with increasing entrained air content, and both the total and ash retentions fell. Presumably, the large surface area of the air bubbles adsorbed some of the retention aid and thus reduced its effectiveness. In addition it is likely that the impaired drainage with increased air amount cause increase in share forces, which disturbs the effect of retention aid polymers.

The pilot paper machine trials permit no clear conclusions to be drawn on the effect of entrained air on tear strength, formation, roughness and initial wet strength. In agreement with previous studies by Kirchner, the drainage time, porosity, smoothness, tensile strength and initial wet strength decreased slightly in the trials /1/.

The effect of the defoamer in the trials was the same as with the trial points with the same air content (Paper IV). In addition to the advantages gained by reducing the entrained air content, the defoamer slightly reduced the numbers of spots and pinholes and also resulted in slightly lower porosity compared with trial points with the same entrained air content but without defoamer.

These research results cannot be applied directly to any particular paper machine, which would be the case even if the trials had been conducted on a commercial paper machine. Every paper machine has its own characteristics – such as its construction and the raw materials used. The results in this study give a fairly good idea of the quantitative effects of entrained air, even for a commercial paper machine. The results indicate how strongly the different papermaking properties are affected by entrained gas (Paper IV).

The pilot paper machine used in these trials had a slow production speed, which is below the present production speeds on modern paper machines. However, the results should be very similar to commercial Fourdriner or top former paper machines, even with higher production speeds. /56/

Many of today’s paper machines have a gap former. Lamminen has conducted pilot trials with a gap former with newsprint furnish with a production speed of 1380 m/min, which is very similar to today’s modern commercial gap former used in printing and writing paper machines. There the air had only a little effect on drainage; the turbulence in the gap may be so high that small bubbles do not affect the formation of the web. /14/

Even if the drainage in the gap former would not weaken harmfully by the high air content, the air would probably cause foaming, unwanted flotation of fibres, increased pulsations in the approach flow system, impaired use of retention aids and other chemicals as well as adsorption of hydrophobic trash on air bubbles, which can cause spots and breaks on paper web.

6.4. Effect of precipitated gas on papermaking

The objective of this study was to determine if precipitated gas bubbles affect papermaking in a different way compared with entrained gas which mostly consists of free gas bubbles (Paper IV). The study was carried out using a Moving Belt Drainage Tester (MBDT). The sample was a headbox furnish from a commercial paper machine producing MFC paper. A commercial paper machine furnish was used in order to cover all the compounds present in normal papermaking. No hydrophobic sizing was used on the MFC paper machine (Paper V).

The MBDT is different from a traditional sheet mould; the drainage is pulsed as on a commercial paper machine. On a paper machine, the pulses are caused by foils under the moving wire. In a MBDT, the pulses are caused by a cocked belt, which moves against a stationary suction box and a stationary wire. In other words, its design is inverted compared with a normal paper machine, Figure 6.8. Previous MBDT trial results have correlated very well with those of Fourdriner paper machines, even at full production speeds /57,58,59/.

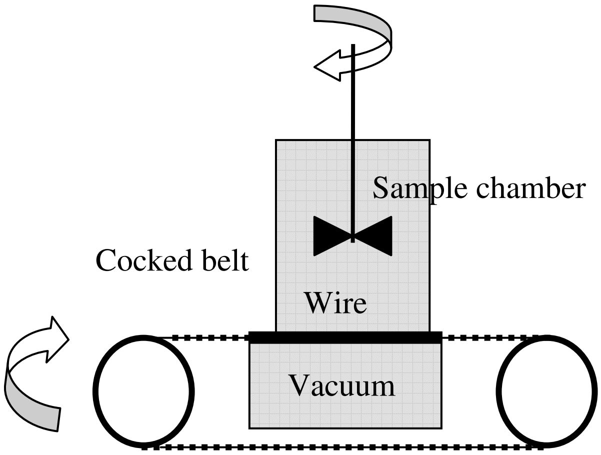

Figure 6.8. Moving Belt Drainage Tester (MBDT). The sheet is formed on top of the wire.

In the Moving Belt Drainage Tester (MBDT) trials, the process conditions were kept constant as far as possible. The only variable used was the entrained air content.

The MFC paper stock consisted of pine chemical pulp and spruce thermomechanical pulp (TMP), calcium carbonate pigments, fixative, PAM, bentonite, alum, defoamer and some calcium carbonate, clay and latex from coated broke. The pH was 7.5. The mill uses the wire pit and a vacuum deaerator and chemical deaerator to remove gas from the wet end process.

The sample furnish was aerated in a pressurised tank to increase the entrained air content. The temperature in the vessel was adjusted to 50°C with a temperature sensor and a heating element. The sample was aerated for a minimum of ten minutes to saturate it with dissolved air, and the aerated sample was led from the pressurised tank to the MBDT sample chamber for the trials. At atmospheric pressure, the dissolved air in the sample fibre suspension is precipitated into entrained air (Paper V).

The gas content of the sample stock in the MBDT trials was measured before and after aeration with a gas meter working according to the compression method. The following properties were measured from the MBDT trial sheets: solids content, tensile and tear strength, porosity, roughness, wet tensile strength, density, grammage and ash content (Paper V).

The following conclusions can be drawn from the results obtained in the Moving Belt Drainage Tester (MBDT) trials, in which the entrained air content was increased with the aid of precipitated air. The drainage was significantly reduced by entrained air, so the vacuum decreased in the MBDT, Figure 6.9.

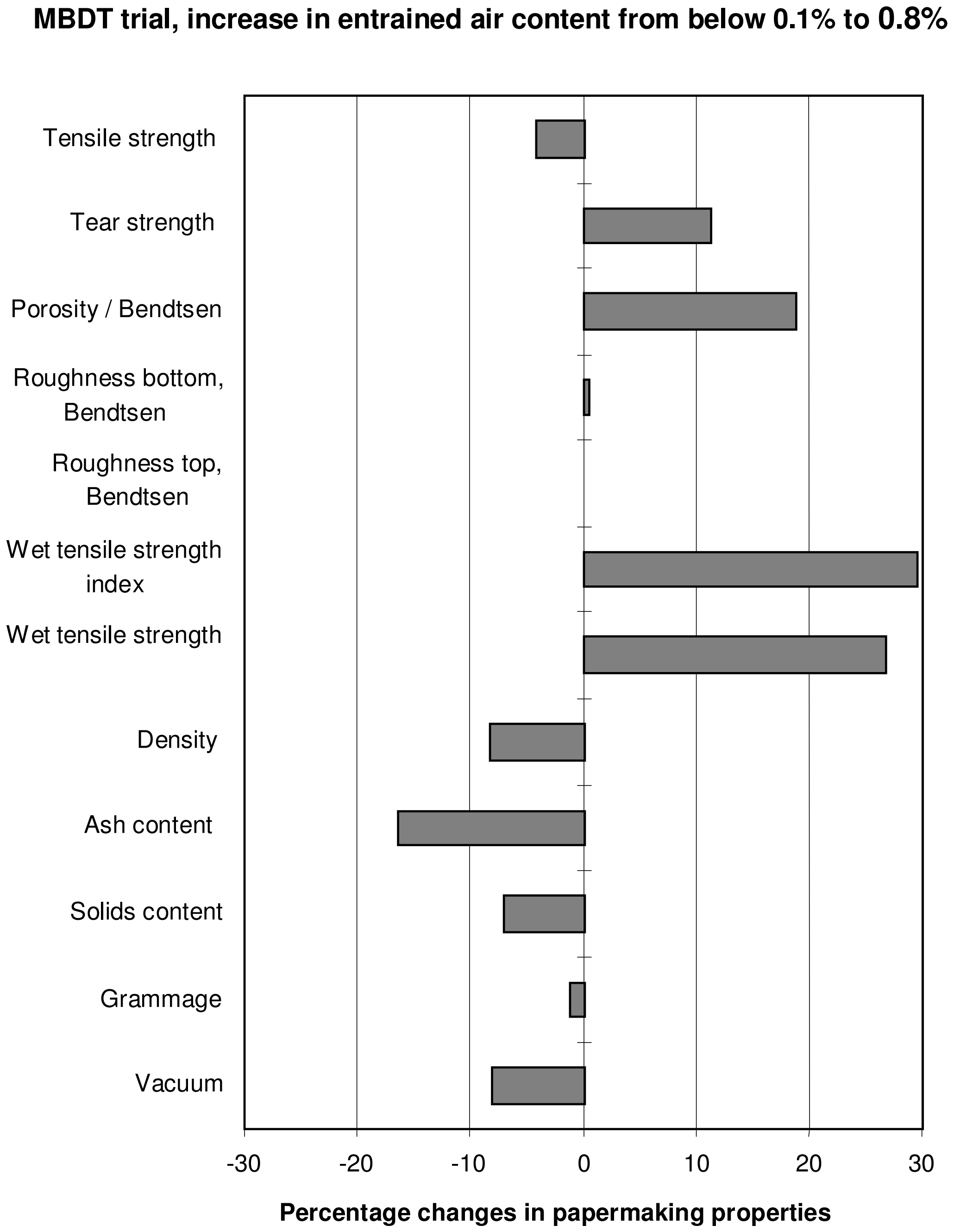

Figure 6.9. Effect of raising entrained air content from below 0.1% to 0.8% on different properties in a Moving Belt Drainage Tester (MBDT) trial. Percentage changes from average values of papermaking properties measured from paper sheet samples.

Porosity, tear strength and wet tensile strength increased in these trials. The bound air bubbles in the fibre network probably enhanced porosity and wet tensile strength. The wet tensile strength could have been somewhat increased by the surface tension of the bound gas bubbles. The increase in tear strength could be explained by the decreased amount of filler as well as by increase in the amount of fines and the number of bonds in the paper web, caused by flotation. There is an optimum amount of fines for tear strength, so the flotation could in some cases also reduce the tear strength.

Ash, total retention and density all decreased. The large surface area of the air bubbles presumably adsorbed some of the retention aid, reducing the retention values. The density was reduced by the lower ash content and increased porosity. No definite conclusions regarding the effect of entrained air on roughness and tensile strength can be drawn based on the MBDT trial.

Precipitated gas bubbles appeared to have largely the same effect on papermaking as dispersed gas bubbles in the pilot trial described in chapter 6.3. However, some differences were found compared to the findings of previous studies made with dispersed gas. Tear strength and wet tensile strength have not been found to increase in the presence of dispersed gas bubbles, but they were improved by precipitated gas in these MBDT trials. This could have been caused by the large amount of bound gas bubbles in precipitated gas (Paper I).

Both dispersed and precipitated gas bubbles had mostly negative effects on papermaking. Only a few positive effects were found, so in general, the gas content in the fibre suspension should be minimised (Paper V).

7. CONCLUSIONS

The objective of this dissertation was to characterise gas in papermaking and to study the effects of centrifugal force on flotation fibre recovery and the removal of gases from fibre suspensions. In order to reach these goals, laboratory and pilot paper machine trials with dispersed and precipitated gas bubbles were carried out. Laboratory and mill trials subjecting the fibre suspension to centrifugal force were also made.

The approach in the experimental work of this thesis was based on three hypotheses, which can be phrased as follows:

1. Flotation fibre recovery can be significantly increased with centrifugal force.

2. Gas can be removed effectively enough from the papermaking fibre suspension with centrifugal force.

3. Complete gas removal is not needed in papermaking.

Two of the hypotheses were valid. However, the first hypothesis was found to be invalid. Based on the laboratory, pilot and mill trial results, the following conclusions could be drawn:

1. Centrifugal force cannot be used on the paper machine to improve significantly the efficiency of dissolved air flotation, i.e. fibre recovery.

   Nevertheless, it was found that in microflotation dispersed gas bubbles did not adsorb on fibres, fines and pigments, whereas precipitated gas bubbles were formed on fibres, fines and pigments. Similar pressure changes as in dissolved air flotation, i.e. DAF, can take place in practical papermaking conditions. This means that dissolved gas can easily precipitate into solids.

2. Centrifugal force removed practically all the entrained gas, i.e. gas bubbles, from the fibre suspension.

   Centrifugal force did not remove dissolved gas. However, it is possible to precipitate dissolved gas into gas bubbles, for example with the aid of turbulence, after which the gas could be removed with centrifugal force. In addition, if vacuum is used during centrifugal degassing, practically all the entrained gas is removed at that pressure. When the pressure returns to atmospheric pressure after degassing, some of the dissolved gas has been removed.

3. Even low entrained gas contents had adverse effects on papermaking, such as impaired drainage, occurrence of pinholes, foam, spots from flotated impurities and adsorption of surface-active chemicals due to the large surface area. Precipitated gas bubbles appeared to have largely the same effect as dispersed gas bubbles. Some differences were found in their effects on tear and wet tensile strength, which were slightly improved. All in all, the results show that in general the entrained gas content in a papermaking fibre suspension should be minimised.

   The precipitation of dissolved gas into gas bubbles must be prevented. However, dissolved gas removal is not necessary for papermaking, provided that the process is correctly designed. If all the entrained gas is removed right after the wire section, this entrained gas cannot convert into dissolved gas at the bottom of the wire pit or in the pipelines. Furthermore, the dissolved gas cannot convert back to entrained gas in the headbox as a consequence of pressure changes in the short circulation. This means that centrifugal force, i.e. the “pomp” centrifugal pump, can be used in papermaking for effective deaeration of the fibre suspension, even without the help of turbulence or vacuum.

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