The Role of Suction Boxes on Forming Section Retention and Filler Migration

by

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Abstract

An apparatus was constructed to observe fibre mat formation under applied vacuum pressure comparable to that experienced in a suction box. The main focus of study was to determine the effects of system parameters on overall retention, filler distribution, and filler migration by analysing samples through weighing, ashing and EDX analysis.

It was found that increasing suction pressure slightly decreased the overall retention, although the effect was greater at higher filler loadings. The forming fabric selection was statistically significant in determining the overall retention, and the significance of forming fabric selection grows with increasing filler loading. The most important factor in determining overall retention was the presence of retention aids. Measurement of the instantaneous permeability of the forming fabric and fibre mat during the forming process showed differences in the permeability curves between forming fabrics, particularly during the initial forming process. The permeability variations are correlated with differences in retention. Tests performed under gravity drainage, to provide a correlation between fabric properties and overall retention results, showed that air permeability had the highest correlation.

Sheet splitting and ashing hand sheets formed using cationic PCC filler showed that applying a vacuum during the drainage process decreased the average filler content. The filler was preferentially removed from the wire side of the sheet. Similar tests performed with anionic filler showed that filler charge affects the distribution in a hand sheet. Anionic filler also showed little change in distribution when vacuum was applied during forming. Cationic and anionic filler have different retention mechanisms; attachment and filtration, respectively. Applied vacuum was found to affect the filler distribution of particles retained by attachment with the highest changes at the wire side. Applied vacuum was found to have only a small affect on particles retained by filtration. The reason for both is the compaction of the fibre mat, which occurs to the greatest extent at the wire side. The compaction reduces the size of openings in the mat which will further trap large particles retained by filtration but increase the drag on small particles, possibly exceeding the attractive forces responsible for attachment to the pulp fibres.

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Co-Authorship Statement

The authors of Chapter 2 are James Montgomery, Sheldon Green, and Alois Vanerek. Dr. Green identified the need for further information regarding retention during suction box forming. I determined the research variables to be tested (suction pressure, forming fabric selection and addition of retention aids) and the method for performing these tests with the supervision of Dr. Green. I performed all of the experimental testing for the research. With direction from Dr. Green and Dr. Vanerek, I performed data analysis to determine the effects of the research variables and provided conclusions regarding the meaning of the results. I wrote the manuscript with revisions and suggestions from Dr. Green and Dr. Vanerek.

The authors of Chapter 3 are James Montgomery, Sheldon Green, Alois Vanerek, and Jimmy Jong. Dr. Jong identified the need for further information regarding filler migration during suction box forming. Dr. Green identified the possibility of forming hand sheets in two parts to determine migration of filler particles from top side to wire side of the sheet. I determined the research variables to be tested (gravity and vacuum drainage, two filler types, consistency, and retention aids), the method for performing these tests and the analysis. I formed all of the hand sheets and performed the SEM/EDX analysis of filler content. The hand sheet ashing was performed at FP Innovations in Point-Claire, Quebec. With direction from Dr. Green I performed data analysis to determine the effects of the research variables and provided conclusions regarding the meaning of the results. I wrote the manuscript with revisions and suggestions from Dr. Green, Dr. Vanerek and Dr. Jong.

Chapter 1 - Introduction

1.1 Introduction to Papermaking

The concept of papermaking has been around for centuries in various forms. Modern papermaking can be said to have come about at the end of the 18th century with the patenting of the first continuous papermaking machine in France [1]. The basic method of making paper is to create a dilute suspension of pulp fibres (typically wood pulp) in water and drain the suspension through a wire or mesh (often called the forming fabric). The remaining wet mat of pulp fibres, once dried, can be used as a sheet of paper. In modern paper mills this process is performed continuously, at rapid speeds, using large-scale industrial equipment specialized to produce a specific type of paper product that can vary from newsprint to liner board to tissue paper.

In addition to pulp fibres, a number of additives are included in the typical pulp suspension. The components added to the suspension can be either mineral or chemical and serve to increase the final sheet properties, or aid in sheet formation or solids retention. There are a wide variety of chemical additives that can be used in the process depending on the desired results. Some of the possibilities include; pH control, retention aids, flocculants, drainage aids and a variety of specialty chemicals [1]. The specific chemicals, quantities used and order of addition greatly affect the final paper properties. Chemical additives and their effects on the papermaking process have been extensively studied by many authors, an overview of the fundamentals of papermaking chemistry has been provided by Lindstrom [2]. Typical mineral additives include starches, clay, talc and calcium carbonate. These additives affect the final sheet properties such as burst and tensile strength, opacity, brightness, smoothness, printability, and formation [3-5]. Further information on mineral fillers will be discussed in Section 1.3.

The paper machine can be broken into five fundamental sections that each play a critical role in the papermaking process; the approach section, the dewatering section (also called the forming section), the pressing section, the drying section and the finishing section. The approach section consists of the pumping, mixing and diluting of the pulp suspension to the appropriate levels for the process of papermaking. There are also cleaning and screening processes that can occur before the pulp is permitted to enter the headbox. At this point in the process the solids content in the pulp suspension is approximately 0.5% [6]. The headbox is at the beginning of the paper machine and serves the function of discharging a uniform jet of pulp suspension evenly onto the forming fabric. The forming fabric serves as a screen through which the water in the pulp suspension drains, depositing a wet pulp mat. The drainage of water through the forming fabric is aided by a number of drainage elements that provide varying pressure magnitudes and profiles that act to both draw water through the forming fabric as well as to influence the forming characteristics of the paper. The drainage elements include: hydrofoils, table rolls, suction boxes, dandy roll, and couch roll, and vary between paper machines in quantity and order. A diagram of the forming section of a Fourdrinier paper machine can be seen in Figure 1. After the forming section, wherein as much water is removed from the pulp suspension as possible by means of gravity and suction drainage, the wet pulp mat then passes through the pressing section. The solids content in the wet fibre web at the end of the dewatering section is 20-25% [7]. In the pressing section the paper is pressed, usually between two rolls, to remove water that could not be removed in the drainage section due to the vacuum forces. The water is squeezed from the pulp suspension into a felt that passes between the pulp mat and the press rolls. After the pressing section the pulp mat, at a solids content of 40-50% [7], passes into the drying section for the final step of water removal by evaporation. The drying section consists of numerous heated rolls, blowers and ventilators that act to heat the pulp mat and evaporate the remaining water to reach a solids content of 90-95% [7]. The final section of the paper machine is the finishing section. This section can vary considerably between paper machines and contains the components to perform functions such as calendaring, reeling and cutting in preparation for the end use.

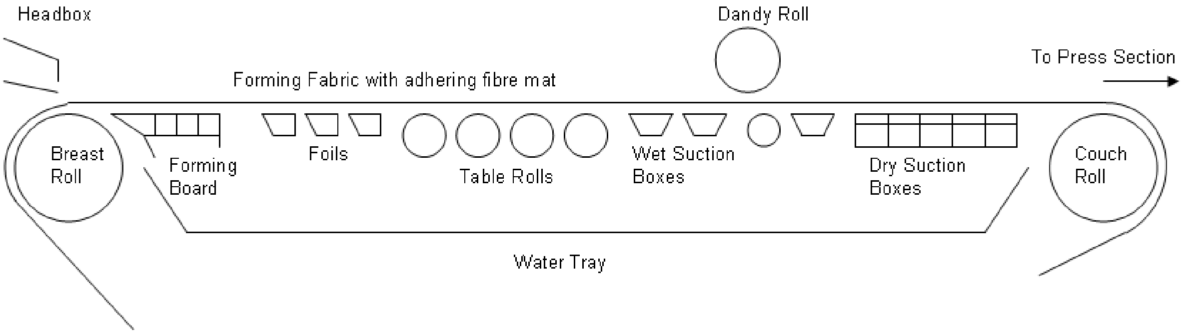

Figure 1: Forming section of a Fourdrinier paper machine

The forming section on the paper machine can be of different design types depending on the type of sheet made and the properties required. The most simple type of former is the Fourdrinier paper machine. Fourdrinier paper machines are characterized by a single horizontal forming fabric that runs in a continuous loop onto which the pulp suspension is dispersed and the water drains through vertically. This is the more simple design type and it involves single sided dewatering which results in two-sidedness of the paper sheet (the two surfaces having different properties) [8]. The basic forming section of the paper machine has undergone many innovations since the early design of the Fourdrinier machine. The innovations have led to more complex, faster machines with wider spans that allow for increased production. The more complex Twin-wire (or gap) formers contain two forming fabrics between which the pulp suspension is deposited via an impingement jet. Twin-wire forming is a more complex procedure but allows for dewatering through both fabrics which eliminates two-sidedness and increases dewatering speeds. Beyond the initial transfer of pulp suspension from the headbox to the fabric, the two types of paper machines contain similar components and sections as outline above.

1.2 Suction (or Vacuum) Boxes

In the initial stages of the dewatering section of the paper machine the suspension is sufficiently dilute to allow for the gravity drainage of water. As the water drains and the solids content in the pulp suspension increases, pulp fibres are deposited on the forming fabric and the resistance to drainage increases. At a solids content of approximately 5% [9,10] the resistance is too high for further drainage by gravity. At this point suction is required to attain a higher solids content in the fibre mat and can be applied by passing the forming fabric over a suction (or vacuum) box. Suction boxes are used both before and after the 5% consistency mark to regulate mat formation and dewatering.

Suction boxes are troughs below the forming fabric with slotted or perforated covers that are connected to a vacuum system. A diagram of a suction box can be seen in Figure 2. As the forming fabric with adhering fibre mat passes over the suction box the pressure differential between the atmosphere and the vacuum system is applied to the pulp suspension and causes drainage [6]. After the applied suction box dewatering the solids content in the fibre mat can reach between 15 and 25% [9,10] and is dependent on the pulp properties and the applied suction. In a paper machine there are typically a number of suction boxes over which the forming fabric passes. This provides a pulsing action of applied suction. The vacuum pressure in a suction box can be controlled to vary the pressure in individual suction boxes thereby controlling the pressure profile to which the pulp suspension and wet fibre mat is exposed. Typical pressures utilized in suction boxes are between -15kPa and -50kPa [6,9,10] but may be as low as -70kPa on modern high-speed paper formers [9]. The applied suction level controls the magnitude and profile of the drainage throughout the section of the paper machine containing suction boxes. Characteristics of the suction boxes that affect the sheet water content include the magnitude of the suction, the suction pulse length (related to machine speed and suction box slot width) and the frequency of suction pulses [11,12]. It was also found that gradually increasing the applied suction in successive suction boxes provides advantages by drying the sheet more efficiently [11]. Characteristics of the pulp furnish that affect performance of a suction box include pulp type, basis weight, consistency of sheet passing over the vacuum box, freeness, fines content, temperature, etc.[9,12].

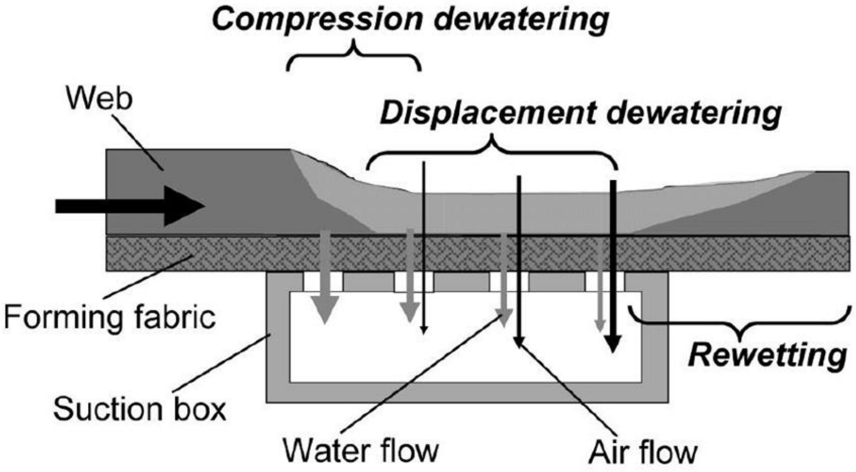

Figure 2: Dewatering mechanisms in a suction box [10]

The change in water content in a suction box is attributed to three mechanisms: compression of the fibre web, displacement of water by air, and rewetting. As the forming fabric and fibre mat pass over the suction box the pressure difference causes compression in the fibre mat. This web compression forces water to flow from the fibre mat through the forming fabric and into the suction box. The applied suction and web compression is accompanied by air flow through the fibre mat and forming fabric. Airflow displaces water in the fibre mat and carries it through to the suction box. Finally as the forming fabric and fibre mat leave the suction box the fibre mat expands and draws water from the forming fabric to the fibre mat causing a rewetting [10]. A diagram of the three mechanisms of dewatering can be seen in Figure 2.

The literature is lacking in investigations of the affect of applied suction on retention of solids during forming. Discussion of the research into retention during forming with and without suction is provided in Section 1.4.

1.3 Mineral Filler

There has been a recent trend in the industry to increase filler content in paper. Addition of filler to paper increases the brightness and opacity, reduces surface roughness and thereby increases the printability of paper. Increasing the filler content in the pulp suspension and final sheet has complex effects on the forming properties, such as drainage, retention, and permeability, in the paper machine wet end [3-5]. The forming properties of the sheet depend on the filler type used, the loading and the distribution in the sheet and pulp suspension. The benefits of increasing the filler content in paper extend beyond the sheet properties. There are also economic and energy efficiency benefits to increasing filler content. Typical fillers cost less than pulp fibres and do not require refining, a large consumer of energy. Wet fibre mats with higher filler contents may leave the press section at higher solids contents, and therefore require less drying energy than less highly filled paper [7]. At a given sheet basis weight, more highly filled papers will cost less to produce.

Calcium carbonate ($CaCO_3$) is a common mineral filler that is used extensively in the papermaking process. The main purpose of $CaCO_3$ in papermaking is to improve opacity, brightness, ink receptivity and surface smoothness [3]. There are two types of $CaCO_3$ filler used; ground calcium carbonate (GCC) which is typically ground limestone or calcite, and precipitated calcium carbonate (PCC). GCC is manufactured in either a wet or dry process depending on desired particle size and results in a random particle shape [13,14]. One of the problems associated with the use of GCC is the presence of impurities such as iron and silica. PCC is a synthetically manufactured calcium carbonate that can be produced on site at the paper mill and is characterized by high purity, often >96%. The size and shape of PCC particles can be tightly controlled and depends on the manufacturing method employed. Typical shapes of PCC particles are rhombohedral (barrel-shaped), scalenohedral (rosette-shaped) and acicular (needle-like) [13,14]. The increased optical properties of PCC (brightness level and scattering coefficient) over GCC and clays has led to its widespread use as a paper filler [15].

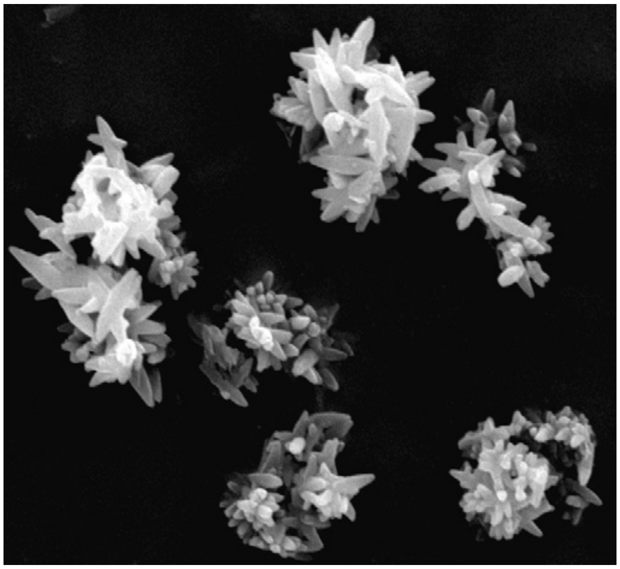

Figure 3: Scalenohedral precipitated calcium carbonate (PCC) [4]

The surface charge of calcium carbonate is an important factor in its use in the papermaking process. $CaCO_3$ can attach to wood fibres in the pulp stock suspension if the components have favourable chemical charges. Pulp fibre in the paper machine stock is anionic [16] and, in general, anionic $CaCO_3$ is repelled from the fibre surface whereas cationic $CaCO_3$ is attracted to the pulp fibres [17,18]. The surface charge of the components can be affected by various system parameters. Both GCC and PCC are positively charged when dispersed in distilled water and negatively charged in tap and white water [19]. The surface charge is also affected by pH, concentration, time in suspension, surface area of particles, and addition of polymers [19-21]. An important factor that is controlled by the charge of filler particles is the size of the aggrogates. At low charges (near neutral), $CaCO_3$ is unstable and forms large aggrogates. At higher charges, both anionic and cationic, electrostatic forces repel $CaCO_3$ particles and prevent the formation of aggrogates which causes increasingly smaller particle sizes [19,21].

Another filler used in papermaking is ground clay. Clay is a naturally occurring substance that is mined for use in papermaking. The clay used in papermaking is a hydrated aluminum silicate ($Al_2Si_2O_5(OH)_6$). Clay has many of the same benefits and properties as ground calcium carbonate filler [22]. Since clay is naturally occurring the particle shape cannot be controlled to the same tight specifications as PCC. Clay particles used for filler are typically hexagonal shaped with a size range between 2-20μm [22]. Though the benefits of clay as a filler are not as great as those of PCC it finds use because of ready availability and cost effectiveness.

1.4 Retention and Chemical Retention Aids

Retention in the papermaking process is the percentage of solids initially added in the pulp suspension that remains in the final product. In hand sheet forming this is determined by comparing the oven dry weight of the final sheet with the known amount of solids initially added to form the hand sheet. Increasing the retention during papermaking is of great importance because a system with higher retention will require less initial material to create a sheet of given basis weight, therefore reducing the cost of production. There are a large number of factors that affect the retention during sheet forming including pulp furnish, machine speed, temperature, fillers, applied suction, chemical retention aids, basis weight, consistency, particle affinity, forming fabric structure, etc. [23-25]. The different solids in the pulp suspension have different rates of retention based on their sizes relative to the size of opening in the forming fabric used. Pulp fibre length is on the order of 0.5–2 mm [26] which is much larger than typical frame sizes of 100-400 microns seen in modern forming fabrics. Filler particles (0.2-15 microns [26]) are significantly smaller than the forming fabric openings and therefore are not directly retained by the forming fabric itself but by the fibre mat as it is built up. The mechanisms by which the fibre mat acts to retain filler and fines particles are electrostatic attraction (attachment), filtration, sedimentation, and flocculation [27-33]. It has been reported that the primary mechanism for filler retention is attachment by chemical interaction, or van der Waals electrostatic forces, and that the other mechanisms are of secondary importance [33,34]. These forces are greatly increased by chemical retention aids and therefore a great deal of focus has been placed on the use of chemical retention aids.

A chemical retention aid is any substance added in the papermaking process that increases the retention of fibres, fines, or fillers [28]. Most retention aids cause increased retention by one of two methods; macromolecular bridging or charge modification [17,25,35,36]. The function of both methods of chemical retention aids is to cause increased flocculation in the system (fibre-fibre, fibre-filler and filler-filler flocculation) by making use of attraction of oppositely charged particles and providing chemical modifications and interactions to optimize the benefits obtained. The method that is induced due to the addition of chemical retention aids depends on the properties of the chemical retention aid. It is generally accepted that high charge density retention aids will act through charge modification and high molecular weight retention aids will act through macromolecular bridging [2,37]. There is a wide variety of chemical retention aids used in papermaking. A few examples of popular types are monopolymer systems, dual polymer systems, and microparticulate flocculation systems [2].

The benefits of increasing filler content in paper has led to research investigating the effects of various system parameters on the retention of filler products. A large portion of this research is in the area of chemical retention aids and how these chemicals can increase the amount of filler attached to wood fibres. In these studies the percent of filler electrostatically attached to pulp fibre is used as a retention value. Some studies [17,18,38] perform investigations of this retention in a dilute pulp suspension where no hydrodynamic shear is present. These neglect the important effects that hydrodynamic forces have on retention by attachment of filler to the pulp fibres and the breakup of flocs and agglomerates. Additional studies have utilized a dynamic drainage jar (DDJ) to incorporate the effects of hydrodynamic shear and have been performed both without [25,27,28,35,39-42] and with [30,42] an applied vacuum. These studies implicitly assume that the primary mechanism of filler retention is through electrostatic and chemical interactions; they do not allow for the retention effects associated with a fibre mat. The forming of the pulp mat changes the dynamics of the system by providing non-uniform flow and increasing local flow rates throughout the sheet as the mat builds up. The fibre mat is also directly responsible for retention of filler particles through filtration and sedimentation. Those experiments that have been performed using fibre mats have either consisted of deposition on a preformed fibre mat [34,43,44] or have not included the effects of varying vacuum levels in the forming process [30,45]. An investigation into the affects of applied vacuum is important to the literature because all paper is formed by applying a suction at some point in the process.

1.5 Z-direction Filler Distribution

Z-directional filler distribution refers to the differences in filler concentrations through the thickness of a sheet of paper. Different paper end uses require different filler distributions for optimum characteristics. Injet printing, coated paper and supercalendered paper grades require high filler content on the surface and can accept lower levels in the center [46-49], copy paper requires low filler content on the sheet surfaces and higher filler content in the center [46,47], and offset printing paper requires a constant filler loading throughout the sheet [46].

The distribution of filler in a paper sheet affects a number of the sheet properties. When the filler content on the surface of a sheet is increased there is a decrease in the surface roughness and an increase in the surface brightness [50], both of which are quality improvements. At a constant overall filler loading, the strength of a sheet of paper is increased, and the bending stiffness reduced, when the concentration of filler near the paper surfaces are increased [50]. Printing properties such as ink receptivity, print quality, and dusting are also affected by the filler distribution [51]. Sheet permeability is affected by filler distribution in a complex manner depending on concentration and filler type [4].

The main means of controlling the filler distribution is the method of sheet manufacturing or type of paper machine used. The dewatering conditions during drainage of the pulp suspension are responsible for filler movement and the dewatering conditions are strongly tied to the type of former used. In a standard Fourdrinier paper machine the filler distribution is non-symmetrical with a trend of increasing concentration towards the sheet top side (away from the forming fabric) [46,47,51]. Hybrid formers reduce the top side filler content of a Fourdrinier machine which results in a more symmetrical filler concentration profile [47,54]. Twin-wire formers have a symmetrical filler distribution with a profile that is affected by the applied vacuum in the elements and furnish used [47]. Hand sheet forming results in high filler concentration near the center of the sheet with decreasing concentration towards both the top and wire sides [51,52].

There are other factors that have been investigated for affect on the z-directional filler distribution. One factor that has been extensively studied is the affect of headbox layering, either through layering of the different pulp furnishes or additive layering [46-49]. Layering consists of keeping the feed streams of the pulp suspension to the different layers (typically three when layering is being performed) separate until the forming section. The different layers can consist of variations in pulp furnish, filler percentage or chemical retention aids. By increasing the filler percentage or chemical retention aids in a layer the filler content in that layer of the finished sheet can be increased. Headbox flow rate and dewatering rate have been shown to affect the filler distribution as has sheet basis weight [50]. In gap forming an increase in headbox flow rate resulted in increased top side (away from the roll former) filler content while increasing the blade dewatering shifted filler from the center of the sheet to the surface [50]. As the basis weight of the sheet increases the chance of filler particles being retained by filtration increases. This results in a plateau of constant filler content in the middle of a sheet that is not largely affected by the machine parameters [51].

Two factors that have been studied but were shown to have minimal to no effect on the filler distribution are wet pressing and suction boxes which were shown to change the filler content but not the profile [52,53]. This was prescribed to the filler being fixed in the sheet by the time pressing or suction occurs. The explanation given was that the water content of the sheet was reduced and the mat compacted enough to limit filler mobility. The affect of applied suction during hand sheet forming has also been studied previously [52] and the conclusions drawn were that vacuum did not change the filler distribution in the z-direction. These are both contrary to general observations in the paper mill which suggest that the filler profile is affected by suction boxes and other forming elements.

Though early studies of suction boxes concluded that there was no affect on filler distribution due to the applied vacuum, subsequent investigations have shown that applying a vacuum or changing the suction characteristics during the forming process can change the filler distribution. Increasing the dewatering of loadable blades in a gap former, and therefore increasing the level of pressure pulse and dewatering speeds, can change the filler profile on the sheet side closest to the blades. A medium load decreased the surface and center-plane filler content whereas a high load maintained surface filler content but caused a great decrease in the center-plane [46]. A more recent study investigating vacuum box dewatering on a gap former showed that increasing the suction box vacuum pressure caused reduced surface filler concentration but an increase in the overall filler content [54]. This suggests that other parameters were simultaneously changed. Another author [47] has stated that increasing the vacuum in suction shoes of a gap former caused an increase in the surface content of filler but a decrease in the center-plane filler content though the extent of the changes is dependent on pulp type used. The affect of suction has been of secondary importance in all previous studies. There has yet to be a controlled laboratory investigation focusing on the affect of applied suction on filler distribution. Also absent from the literature is any study investigating how the filler migrates within the sheet to facilitate the changes in filler distribution.

Some work has been performed to try to explain mechanisms within the forming process or sheet properties that affect changes in filler distribution. Correlations in changes of filler distribution and local specific filtration resistance (SFR) due to varying blade loadings in a gap former led Haggblom-Ahnger et al. [46] to propose that the web compaction and increase of SFR leads to increased entrapment of filler. This suggests that changes in filler distribution are dependent on the local SFR in a sheet or the pore sizes between fibres.

Szikla and Paulapuro [53] proposed a number of conditions that would affect the ability for filler particles to move in a sheet during pressing and thus affect the filler distribution. Though their study focused on movement in a fibre mat that had a high solids content, similar principles apply in all areas of the forming process. The conditions that they found were; flow velocity (increasing velocity increases drag on particles), filler content (increasing the number of filler particles increases the likelihood of movement), sheet density (less dense sheets allow for more filler motion), particle size (smaller particles can move through the fibre mat more freely), and state of fibres (increased beating and fibrils caused reduced filler movement). From these studies it has been inferred that for all practical purposes in papermaking the filler distribution is fixed after the dry-line.

There is a diverse array of methods used for determining the z-directional filler distribution in a finished paper sheet. Early investigations used a method of serial grinding of the paper sheet in the z-direction. The remaining sheet substance was ashed and compared with total sheet ash content to determine the ash content of the removed layer [51]. Further development led to sheet splitting using adhesive tape to remove individual fibre layers [54,55]. This allows for the ashing of individual layers to determine the mineral content in each layer. Other analytical techniques have been investigated for potential on- and off-line determination of filler distribution. The use of neutron activation analysis [56] and a combination of X-ray absorption and fluorescence techniques [57] have both been shown to provide accurate filler distribution profiles. More recent development has led to the use of scanning electron microscope (SEM) and energy dispersion x-ray (EDX) techniques to analyze paper cross sections to determine the z-directional filler content [58,59].

1.6 Scanning Electron Microscopy/Energy Dispersion X-ray

Scanning electron microscopy works based on the interaction of high energy electrons with the sample to provide an image of the surface. A primary beam of electrons accelerated to a controlled voltage is directed at the sample specimen and interacts with the atoms on and near the sample surface by transferring some of their energy to the atoms in the sample. Figure 4 shows the interaction of the primary electron beam with the SEM sample. The effects of this interaction (called secondary effects) are the release of secondary electrons, backscatter electrons, or relaxation of excited atoms. Secondary electrons are electrons that escape the sample surface with energies below a certain value (about 50eV [60]). These could be either electrons from the primary beam that have given up most of their energy or electrons from the sample that have been excited by the primary beam. Backscatter electrons are electrons from the primary beam that are ejected from the surface of the sample while maintaining a large fraction of their energy. Backscatter electrons are much less likely to occur than secondary electrons but both are used in SEM imaging. As the electron beam is scanned across the sample the location is recorded and the corresponding intensity of detected electrons produces a greyscale image for output to a computer screen. The intensity of the released electrons is dependent upon the elemental composition of the sample surface in the area being analysed and produces contrast between surface features. The resolution of the image is dependent on the diameter of the electron beam which is controlled by internal condenser lenses to 2-10nm [60-63].

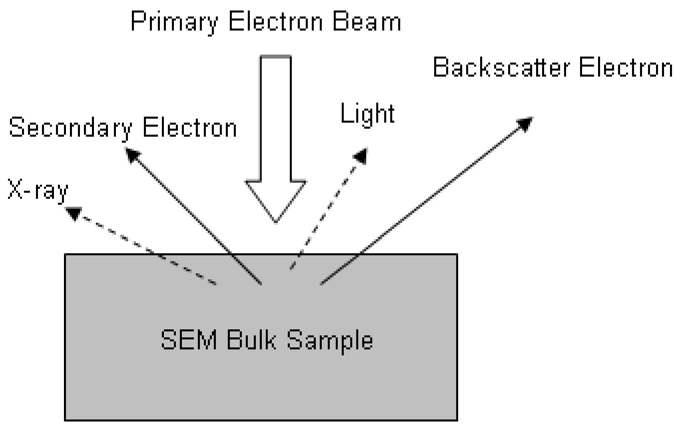

Figure 4: Interaction of the primary electron beam with an SEM sample

Energy dispersion X-ray is an analysis technique that is typically available in modern scanning electron microscopes. EDX provides an elemental breakdown of the sample area over which the primary electron beam is directed. As the primary electron beam interacts with the sample surface it can transfer some of its energy to the electrons of the atoms. These electrons may be excited beyond the binding energy of their orbital shell and ejected from the sample. If an electron is ejected from a lower orbit (closer to the nucleus) then the atom will be considered to be in an excited state and will eventually relax by giving off this excess energy. There are three ways that relaxation of excited atoms can occur. Two of the relaxation methods; cathodoluminescence and release of Auger electrons are not relevant to the context of this study but can be found in the literature [60-65]. The third type of relaxation occurs when an electron from an outer orbit jumps down to fill the inner vacancy. During this jump a characteristic X-ray is released with energy equal to the energy difference between the two shells. This energy is specific to the given electron shells involved and unique for each element. Figure 5 is a diagram of the emission of a characteristic X-ray by an excited atom. It is by collecting the energy from these characteristic X-rays and counting the number of X-rays at each energy level that the EDX analysis can provide details of the weight percentage by element of the sample specimen [60-65].

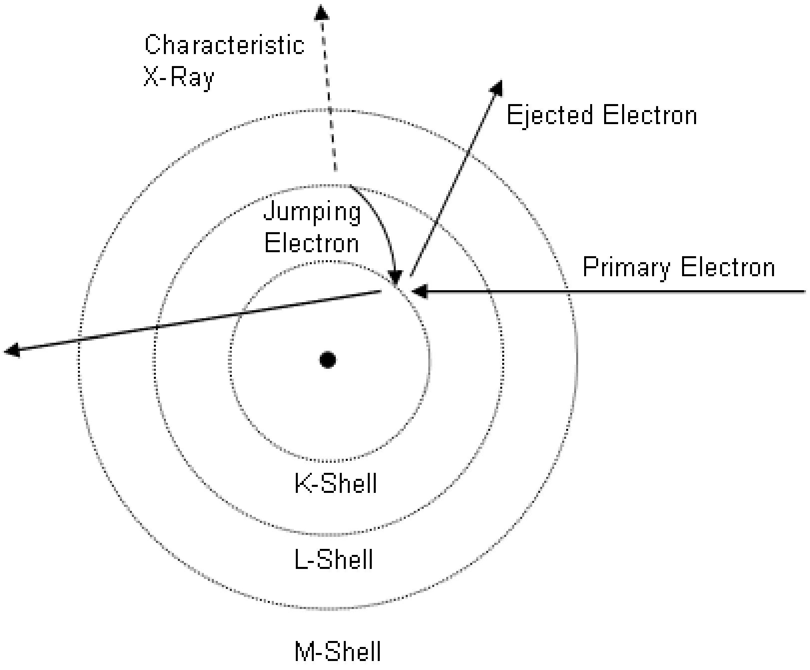

Figure 5: Emission of a characteristic x-ray

The ability of the scanning electron microscope to provide surface images at high resolution and magnification makes it suitable for the use in analysis of paper samples. SEM images have been used in previous studies of paper surface characteristics for both mineral-free paper [66] and coated paper [67] and used for determining the effects that surface structure has on the printability of a paper sheet. SEM has found greater use in the paper industry in analysing the cross section of paper sheets by coupling SEM images with image processing capabilities. The analysis of sheet fibre content in the cross section has been used to determine the location of fines material [68] and sheet pore structure [69]. SEM images of the coated paper cross sections have allowed for determination of surface coating thickness distributions [67], analysis of coating structure [70] and subsequent reconstruction of surface coatings [71]. SEM images have also been used to determine characteristics of individual fibres in the transverse direction such as wall thickness [72].

Energy dispersion X-ray analysis clearly has potential for use in the paper industry because of the complex matrix of organic and inorganic material and the importance of the distribution of this material. Gibbon [73] outlined the possibility of using EDX for the determination of different filler particles in the paper structure and the concentration and distribution of this material. At the time of this original analysis, EDX technology was limited to the detection of elements with atomic number 11 (sodium) and heavier which excluded carbon and oxygen, critical elements in the paper structure. This prohibited the determination of exact weight and weight percentage of the filler particles in the sheet. Further development of EDX technology allowed for detection of all elements with atomic numbers heavier than 4 (beryllium). This lead to EDX being used for the analysis of z-directional filler distribution in paper [58,59].

1.7 Research Objectives

As the pulp and paper industry moves towards further increases in the filler content of paper to facilitate cost reductions a deeper understanding of the retention of these particles is required. There has been a great deal of focus on the effects that chemical retention aids have on filler retention with less focus on the affects of the hydrodynamics. One area in particular that has been overlooked is how the pulp suspension and fibre mat are affected when the forming fabric passes over a suction box. The existing studies neglect the effects that mat formation and increased suction pressure have on retention properties. The overall retention of the solids and the filler retention and distribution may be affected by these parameters.

In order to investigate the affects of vacuum boxes a laboratory scale modified hand sheet former was constructed to allow control and monitoring of the pressure applied to, and the height of, the pulp suspension during forming. Hand sheets allow for testing parameters that are seen on a paper machine under more strict control, for less cost and at a more rapid pace. The modified hand sheet former allowed for testing conditions, such as forming fabrics, suction pressure, and suspension consistency, that matched those used on a paper machine. Details of the design and construction of the apparatus can be found in Appendix A. The first objective of this investigation was to determine the affect that suction boxes, and different parameters in the suction box, had on the overall retention during hand sheet forming and to relate these to paper machine operation where possible. The second objective was to determine how the applied suction in a vacuum box affects the filler particles in the sheet with a focus on the average filler content, filler distribution, and the movement of filler within the sheet.

In Chapter 2 the effects of applied suction, forming fabric selection, and retention aids on overall retention during the forming process are investigated. Instantaneous permeability curves during sheet formation were also investigated to determine differences in mat formation between forming fabrics. Finally, correlations between standard forming fabric design characteristics with the overall retention results were investigated.

In Chapter 3 the effects of applied suction on filler distribution were investigated. The initial investigations focused on the overall changes in distribution. The effects of filler migration during forming from the top side to the wire side were also investigated using different filler types. Separate conclusions were drawn regarding filler motion in paper forming for filler particles with electrostatic repulsion and attraction.

Chapter 4 provides conclusions that can be drawn from the above mentioned experimental studies and describes the contributions to knowledge of this work. The chapter closes with recommendations for future work that can be performed using the apparatus constructed for these investigations.

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Chapter 2 - Effect of Applied Vacuum Box Suction on Overall Retention in Hand Sheet Forming[1]

2.1 Introduction

Paper is produced by dispensing a suspension of wood fibres and various additives, such as calcium carbonate and clay fillers, onto a forming fabric and draining the water by gravity, suction and pressure in a number of processes. One of these processes involves passing the forming fabric over a suction box and applying a pressure difference across the forming fabric and wet pulp suspension to increase dewatering above levels achieved through gravity drainage. A great deal of research has focused on understanding the effect that system parameters such as consistency, pulp furnish, filler, suction strength, pulse length, filler content, retention aids and others have on the final percent dry content in the fibre mat after passing over a suction box [1-8]. More recently, a number of studies have focused on characterizing the mechanisms of water removal from a pulp suspension in the suction box: compression of the fibre web, displacement of water by air and rewetting [9-14]. These investigations were not concerned with the effect of the applied suction on the overall retention of fibres, fines and fillers in the suction box.

As the water is drained through the forming fabric, especially in the presence of a vacuum pulse, a portion of the fibres, fines and filler are pulled through the mat. The overall retention is the percent of solids in the headbox slurry that remains on the forming fabric to comprise the finished paper sheet. There are a large number of factors that affect the retention during sheet forming, including pulp furnish, machine speed, temperature, fillers, applied suction, chemical retention aids, basis weight, consistency, particle affinity, fabric structure, etc. [15-17]. The different solids in the pulp suspension have different rates of retention based on their sizes relative to the size of opening in the forming fabric used. Pulp fibre length is on the order of 0.5–2mm [18] which is much larger than typical frame sizes of 100-400µm seen in modern forming fabrics. Filler particles (0.2-15µm [18]) are significantly smaller than the forming fabric openings and therefore are not directly retained by the forming fabric itself but by the fibre mat as it is built up. The mechanisms by which the fibre mat acts to retain filler particles are electrostatic

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attraction (deposition), filtration, sedimentation, and flocculation. It has been reported that the primary mechanism for filler retention is deposition (or attachment) by chemical interaction (retention aids), or van der Waals electrostatic forces, and that the other mechanisms are of secondary importance [19,20].

There has been a recent trend in the industry to increase filler content in paper. The addition of filler improves the optical properties, smoothness and printability of paper. At the wet end of the paper machine the filler affects the drainage, retention, permeability and other physical characteristics of the fibre mat and finished paper product [21-23]. There are also economic and energy efficiency benefits to increasing filler content. Filler costs less than pulp fibre and the replacement of fibre in the paper sheet with filler particles reduces the cost of paper at a given basis weight. Filler particles do not require refining, which is a process that consumes much energy in mechanical papermaking. Wet fibre mats with higher filler contents may leave the press section at higher solids contents, and therefore require less drying energy than fibre containing less filler [24].

The benefits of increasing filler content in paper has led to research investigating the effects of various system parameters on the retention of filler products. A large portion of this research is in the area of chemical retention aids and how these chemicals can increase the amount of filler attached to wood fibres. In these studies the percent of deposited filler is used as a retention value. Some studies [25-27] perform investigations of this retention in a dilute pulp suspension where only low hydrodynamic shear is present. Additional studies have utilized a dynamic drainage jar (DDJ) to incorporate the effects of hydrodynamic shear and have been performed both without [28-35] and with [36,37] an applied vacuum. These studies implicitly assume that the primary mechanism of filler retention is through electrostatic and chemical interactions; they do not allow for the retention effects associated with a fibre mat. Those experiments that have been performed using fibre mats have either consisted of deposition on a preformed fibre mat [19,38,39] or have not included the effects of varying vacuum levels in the forming process [37,40].

In section 2 we describe a modified hand sheet former that allows for the testing of the effects of suction pressure, forming fabric selection, and the presence of chemical retention aids on the overall retention in the paper forming process with high filler loading. Section 3 presents results related to retention, forming fabrics, and permeability. The paper closes with conclusions.

2.2 Apparatus, Materials and Method

All retention tests were performed in a custom device that has some similarities to a standard hand sheet former. Figure 6 shows a schematic drawing of the apparatus. The apparatus is constructed of a 3” (75mm) diameter, 6” (150mm) tall, clear acrylic circular cylinder below a forming fabric. A flush-mounted gauge pressure transducer (GP:50 Model 218-C-SZ-10-GS) is mounted in the wall of the test chamber below the forming fabric. As described below, the pulp slurry above the forming fabric is exposed to the atmosphere, so the pressure transducer measures the pressure drop across the forming fabric and fibre mat. Another circular cylinder is attached above the forming fabric and a gasket is placed around the outside to provide an airtight seal. An ultrasonic distance sensor (Senix Model TSPC-30S1-232) is mounted above the top portion of the test chamber to measure the pulp suspension height as a function of time, which is used in determining the flow velocity during the forming process. A vacuum chamber constructed of ½” (13mm) thick PVC sheets is connected to the bottom of the test chamber by a ¾” (20mm) PVC pipe and electrically actuated solenoid valve. The vacuum chamber pressure can be adjusted to the desired pressure by an attached vacuum pump.

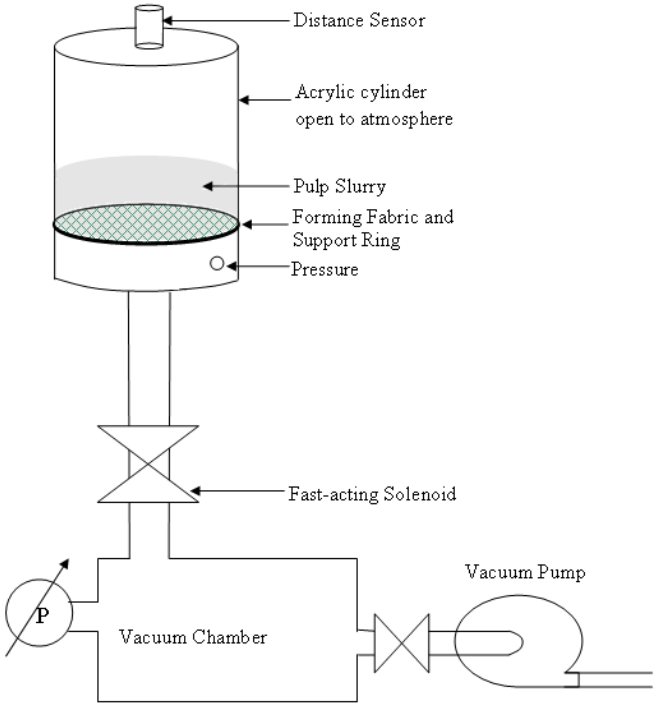

Figure 6: Schematic of modified hand sheet former

Pulp slurry at 0.5% consistency of the appropriate filler content was prepared by dispersing 40g of fibre and filler into 1600mL of 80°C distilled water. The slurry was mixed for 7.5min at 3000rpm and then diluted to 0.5% consistency with additional distilled water. The slurry was refrigerated until use, at which point it was continuously stirred by a laboratory mixer at 250rpm throughout the experiment. This provides a uniformly dispersed mixture with a sampling error of less than 1%. The sampling error was determined by filtering different samples of the slurry through 0.5µm filter paper and measuring the variation in mat weight. To form a hand sheet, distilled water is added to the apparatus between the (closed) valve and the forming fabric. A 60g sample of pulp slurry is measured and the required retention aids added. The sample is transferred into the top cylinder above the forming fabric. A Labview program is used to start the experiment by opening the solenoid valve, exposing the test chamber and pulp suspension to the vacuum pressure. The water in the test chamber drains into the vacuum chamber and a fibre mat is formed on the forming fabric. During dewatering the instantaneous water height above, and the pressure drop across, the forming fabric and fibre mat are recorded. The voltage signals from these sensors are filtered using a low pass filter and written to a file for later analysis. Upon test completion the solenoid valve closes automatically. The fibre mat is removed and oven dried before being weighed.

Hand sheets were formed with and without chemical retention aids from pulp suspensions with filler loadings of 20% or 40%. The pulp used was a softwood, hydrogen peroxide bleached, thermo-mechanical pulp (latency removed, 30% fines) at 0.5% consistency. The filler was Albacar HO (Specialty Minerals Inc.); a scalenohedral precipitated calcium carbonate (PCC) with a manufacturer's listed median particle size of 1.3µm. The chemical retention aids used were cationic polyacrylamide (cPAM) at 0.35kg per ton of pulp and silica at 0.5kg per ton of pulp. The hand sheets were formed on three forming fabrics (listed as 1-3 in Table 1) provided by Asten Johnson (Kanata, Canada). By varying the system parameters described above, as well as the pressure in the vacuum chamber, it was possible to determine the effect of suction pressure, presence of retention aids and forming fabric selection on the overall retention during sheet forming with pulp suspensions of 20% and 40% PCC, representing low and high filler content, respectively.

Table 1: Forming fabric details

				Average Paper Side Frame Size Opening, mm		% Open Area				
Fabric No.	# Layers	Paper Side Weave	Air Perm., cfm (m^3/s)	Finite Yarn	Infinitely Small Yarn	Paper Side	Total	FSI'	Caliper, mm	Drainage Index
1	3	Plain	373 (0.176)	0.149	0.273	30	4.2	209	0.734	39.9
2	3	Plain	392 (0.185)	0.168	0.336	25	3.6	170	0.940	34.2
3	3	Plain	513 (0.242)	0.29	0.531	30.8	4.8	108	1.422	22.5
4	3	Plain	428 (0.202)	0.198	0.346	33.2	5.2	165	0.864	39.6
5	3	Plain	366 (0.173)	0.202	0.357	32.6	4.1	160	0.965	32.2
6 P	1	1, 4 Broken Twill	825 (0.389)	0.389	0.839	38.4	38.4	46	0.965	25.9
6 M	1		825 (0.389)	0.389	0.839	38.4	38.4	49	0.965	25.9

After results were obtained from the above tests, a number of other hand sheets were formed using additional fabrics with more widely varying characteristics in order to correlate fabric characteristics and retention (Section 2.3.2). Further tests were also performed to determine the permeability of the forming fabric and fibre mat using 40% PCC pulp suspension and no chemical retention aids to provide insight into a possible reason for the differences in retention performance (Section 2.3.3).

2.3 Results and Discussion

2.3.1 Overall Retention

Figure 7 shows a typical experimental result. In this figure the pressure drops continuously until the pulp slurry is completely drained through the forming fabric. At this point the pressure rises to a constant value as air is continuously pulled through the fabric and fibre mat into the vacuum chamber. The pulp slurry height drops monotonically. The error bars used in the figure represent the standard deviation of the results and are indicative of the high degree of repeatability of the measurements. The standard deviation of the measurements is greater than the accuracy of the pressure transducer and ultrasonic level sensor. The results for the overall retention experiments are shown in Figure 8 (20% filler) and Figure 9 (40% filler). The three data points for each symbol correspond with three different vacuum chamber settings from 0 to -50kPa. The x-coordinate of each point is the maximum vacuum reading of the pressure transducer during sheet forming. Despite using consistent vacuum chamber settings for each forming fabric, the maximum pressure transducer reading varies from symbol to symbol owing to the varying drainage resistance of each fabric and pulp mat. Each point plotted is the average of five tests performed under identical conditions. The error bars show the standard error of the results.

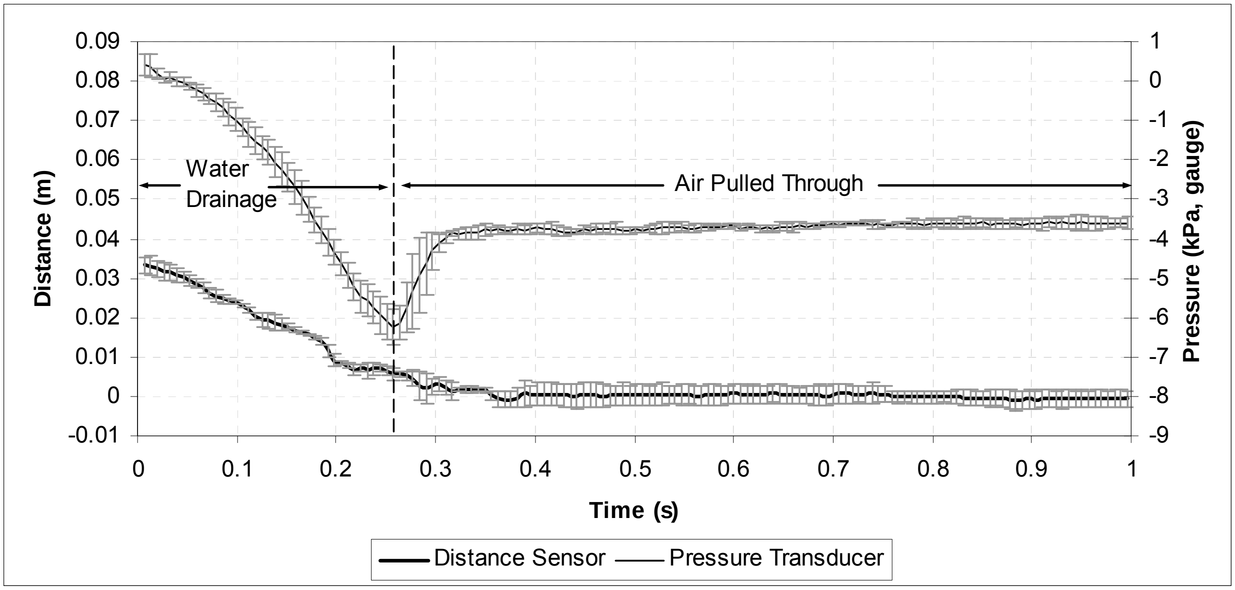

Figure 7: Typical experimental data. The error bars represent the standard deviation measured over multiple trials. The pressure transducer accuracy is ±100Pa and the ultrasonic distance sensor accuracy is ±50μm.

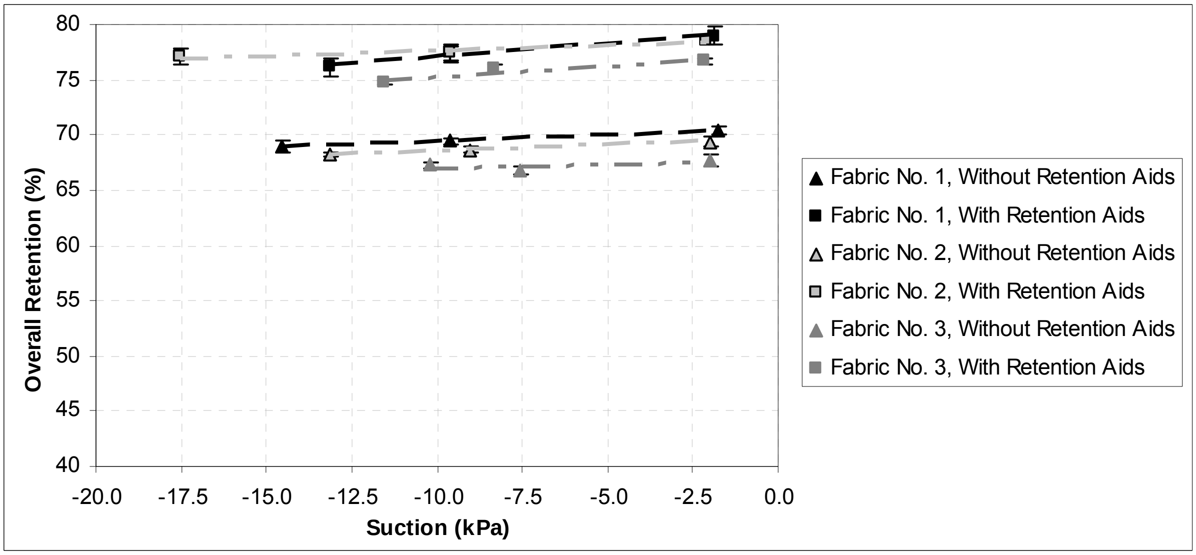

Figure 8: Overall retention versus suction pressure at 20% filler loading

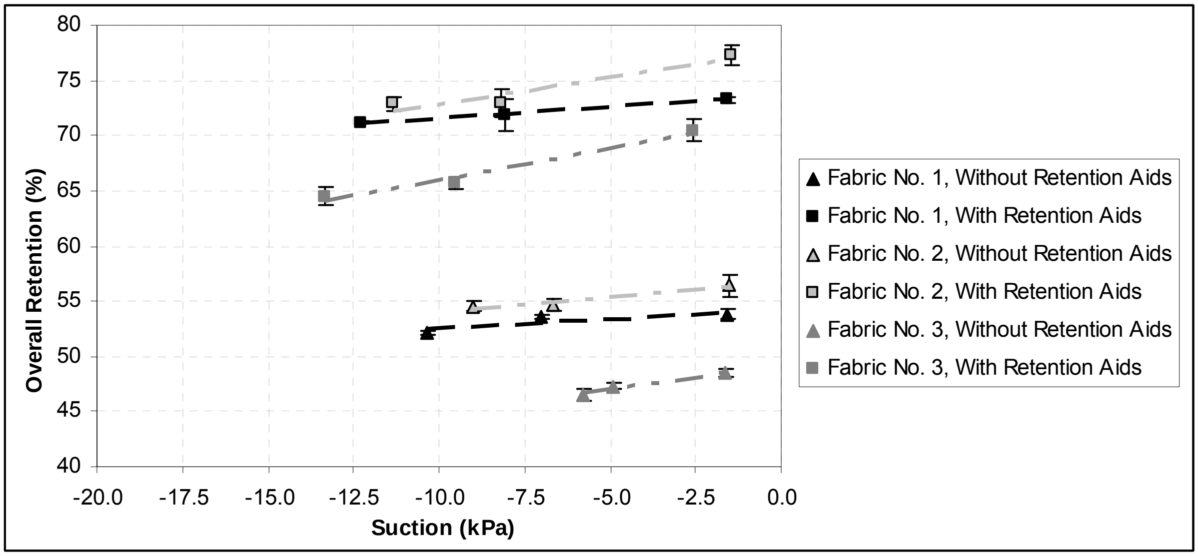

Figure 9: Overall retention versus suction pressure at 40% filler loading

A straight line adequately represents the trend of the overall retention *versus* suction data in Figure 8 and Figure 9. The graphs clearly show that overall retention has a small dependence on applied suction. All of the lines in the graph have a positive slope showing that retention is reduced with increasing suction pressure. Statistical analysis of the uncertainty of the slope shows that the slope of all data sets is positive within a 95% confidence interval. A possible explanation is increased drag during the vacuum drainage. The higher pressure difference causes faster drainage resulting in more drag on particles in the slurry, which can pull embedded fines and filler from the fibre mat. The greater forces might also break flocs and agglomerates, which play a role in increasing retention.

In each of Figure 8 and Figure 9 there are two data sets represented for each forming fabric; one without and one with chemical retention aids. This comprises four sub-groupings of data in which a comparison of effect of the forming fabric on overall retention is possible. The tests performed using 20% filler (Figure 8) both with and without chemical retention aids show that there is little difference between the performance of fabrics 1 and 2 but a striking difference between those two and fabric 3. In the tests with 40% filler pulp suspension (Figure 9) there is a distinct separation between performance of all three forming fabrics. The distinct (statistically significant) separations of the overall retention *versus* suction pressure lines indicate that the forming fabric affects the overall retention results even with the 40-50g/m^2 basis weight of sheets formed in these tests.

Of all the factors that were varied in producing the twelve lines, the presence of retention aids had the greatest effect on overall retention. The addition of retention aids narrowed the performance gap (spacing between the lines) between the forming fabrics as well as significantly increased the overall retention of each fabric. This is consistent with predictions that the dominant method of filler/fines retention is through chemical interactions with fibres and chemical retention aids [19,20].

Comparing the differences in results between Figure 8 and Figure 9 allows for a comparison of the effect of increasing the filler content. It can be seen that a higher filler loading results in lower overall retention. This is because filler particles have a lower retention than pulp fibres. Increasing the filler loading from 20% to 40% also increases the significance of the forming fabric selection as evidenced by the wider spacing between the overall retention *versus* suction pressure lines in Figure 9. This effect is somewhat damped when retention aids are used because chemical retention aids increase the level of filler retention to only slightly below that of fibre retention.

2.3.2 Overall Retention versus Fabric Properties

Figures 8 and 9 show that the forming geometry has an impact on the overall retention results. Knowing this, it would be beneficial to determine a simple correlation between the retention results and fabric geometric properties. In order to obtain meaningful correlations it was necessary to form hand sheets using forming fabrics (listed as 4-6 in Table 1) additional to those used in the previous experiments. Tests were performed using pulp suspensions containing both 20% and 40% filler with gravity drainage, with or without chemical retention aids.

In the past, forming fabrics have been characterized by many different properties including air permeability, caliper, drainage index, fibre support index (FSI), and more. The various properties investigated for a correlation with the overall retention are listed for each fabric in Table 1. For the single layer fabric (fabric 6), properties for the paper side are indicated by ‘P’, and those for the machine side are indicated by ‘M’. The average frame size opening was calculated rather than using the typical manufacturer’s reported frame size (MD frame size) because the fibre orientation in the x,y-plane during hand sheet forming is random. FSI’ was derived by the same method as FSI as described by Beran [41] but using a fibre angle distribution of 1/π, corresponding to randomly distributed fibres in the x,y-plane.

The correlation coefficients for each fabric property tested against the overall retention are shown in Table 2 for the four data sets tested both with and without including the single layer fabric (fabric 6). The fabric property that showed the best correlation with overall retention results was the fabric air permeability. This trend can be seen in Figure 10 for fabrics 1 to 5 as well as an additional single layer forming fabric (fabric 6). The error bars show the standard error. This single layer fabric was tested after the correlation was found between the first five fabrics, to determine if the air permeability trend extended beyond the scope of triple layer forming fabrics. Table 2 shows correlation coefficients for fabrics 1-5 and for fabrics 1-6 to determine the validity of the relations tested both when the single layer fabric is excluded or included. The good correlation is seen even with the single layer forming fabric, which has significantly higher air permeability (825cfm (0.389m^3/s)) than the triple layer fabrics. This trend is seen for all test groupings performed; 20% or 40% PCC pulp suspension, and with or without chemical retention aids. This trend would indicate that the most important factor in determining the retention results of a forming fabric is the air permeability. The correlation with fabric air permeability is not perfect, however, and the deviations may be due to a contribution from the fabric shape characteristics such as weave pattern and frame size. The air permeability of a forming fabric is identical whether the flow is from paper side to machine side or vice versa. Therefore, by performing retention tests with mat formation first on one side, and then on the other side, of the fabric, one gains some insight into the impact of weave pattern on retention.

Table 2: Overall retention versus fabric property correlation coefficients

			Average Paper Side Frame Size Opening		% Open Area				
Fabric Property	Data Set	Air Perm.	Finite Yarn	Infinitely Small Yarn	Paper Side	Total	FSI'	Caliper	Drainage Index
Correlation Coefficient Fabrics 1-5	40%PCC, no RA's	0.8822	0.5799	0.6911	0.0374	0.1358	0.6195	0.6712	0.4764
	40%PCC, yes RA's	0.8033	0.6618	0.5653	0.2766	0.7904	0.4984	0.4275	0.2188
	20%PCC, no RA's	0.8853	0.8608	0.8022	0.1587	0.4755	0.6634	0.7064	0.5182
	20%PCC, yes RA's	0.7807	0.6129	0.5176	0.2786	0.8179	0.4526	0.3814	0.1799
	Average	0.8379	0.6789	0.6441	0.1878	0.5549	0.5585	0.5466	0.3483
Correlation Coefficient Fabrics 1-6	40%PCC, no RA's	0.9651	0.9075	0.9443	0.5241	0.8549	0.9083	0.0690	0.5191
	40%PCC, yes RA's	0.8161	0.8603	0.8039	0.6970	0.6519	0.8083	0.1295	0.4508
	20%PCC, no RA's	0.9892	0.9352	0.9733	0.7368	0.9579	0.8474	0.0201	0.4470
	20%PCC, yes RA's	0.9585	0.9144	0.9443	0.7652	0.8804	0.8719	0.0303	0.4024
	Average	0.9322	0.9044	0.9165	0.6808	0.8363	0.8590	0.0622	0.4548

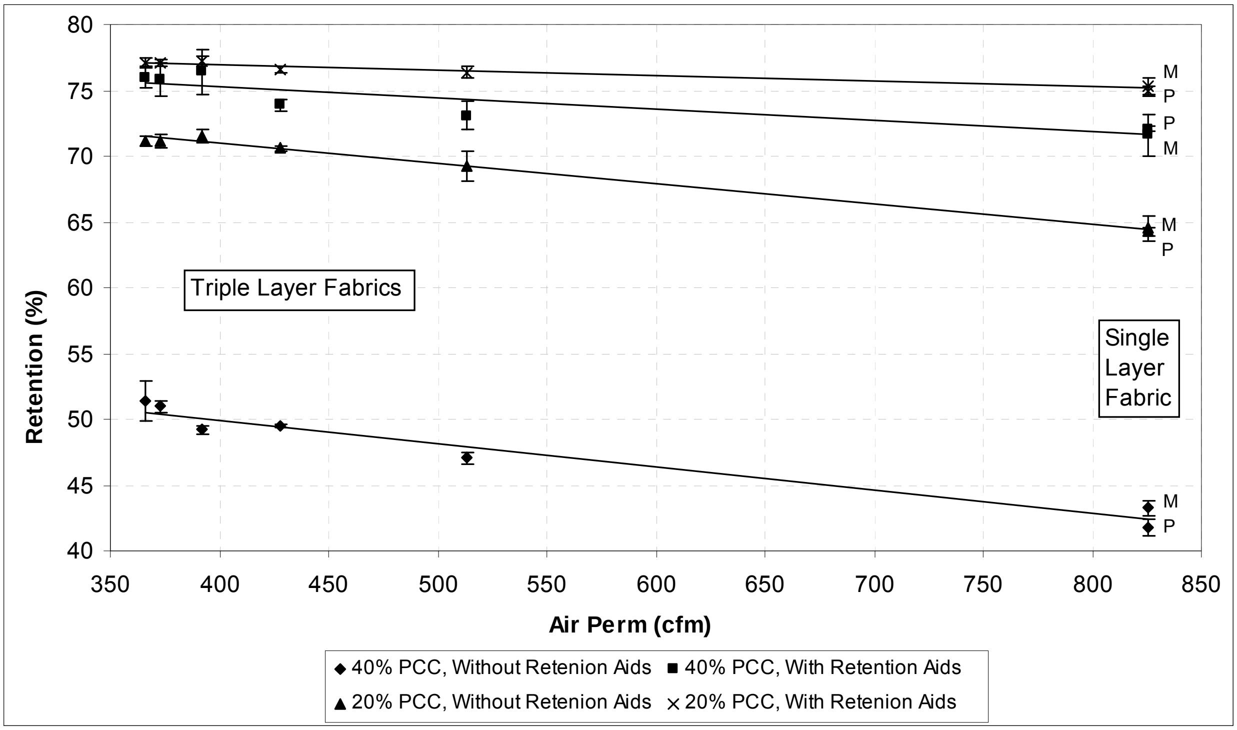

Figure 10: Overall retention versus air permeability

In Figure 10 the results for the single layer fabric with mat formation on the paper side are indicated by ‘P’, and those with mat formation on the machine side are indicated by ‘M’. In no case is there a statistically significant difference in the retention between paper side and machine side mat formation. Hand sheets were also formed on the machine side of triple layer fabrics which have even larger differences in weave pattern and shape geometry. Only very small variations in retention results were found between forming on the machine side or paper side of a triple layer fabric. These findings suggest that weave pattern plays at most a minor role on retention. Because fibres are randomly oriented in the apparatus, but would be more aligned with the machine direction in a real paper machine, it is possible that weave pattern plays a more salient role in paper machine retention.

2.3.3 Permeability Measurements

The apparatus shown in Figure 6 may also be used to measure the permeability, *K*. The permeability, K, is defined as the superficial velocity, V, through fabric and fibre mat divided by the pressure drop, ΔP, across the forming fabric and fibre mat.

$$K = \frac{V}{\Delta P} = \frac{-{dh}/{dt}}{\Delta P}$$

First, pure water (no fibres) was tested in the apparatus, and the permeability of the fabric alone was measured. The measured permeability was within 10% of that extrapolated from measurements in a conventional fabric air permeability measuring device, which lends credence to the use of the apparatus for measurement of permeability.

To shed light on the reason for the difference in overall retention for different fabric selections (which can be correlated to fabric air permeability), hand sheets were formed using a pulp suspension containing 40% PCC under both gravity and high vacuum drainage. The sensor data of water column height, h(t), was fitted with a curve and then the derivative taken to allow for the calculation of instantaneous permeability for each fabric during the sheet forming process. The results for permeability *versus* the drainage ratio of pulp suspension for fabrics 1-3 can be seen in Figure 11 for gravity drainage and Figure 12 for vacuum drainage. The drainage ratio is defined by: drainage ratio = $(h_i-h(t))/(h_i-h_f)$, where h_i is the initial slurry column height, and h_f is the final height of formed pulp mat.

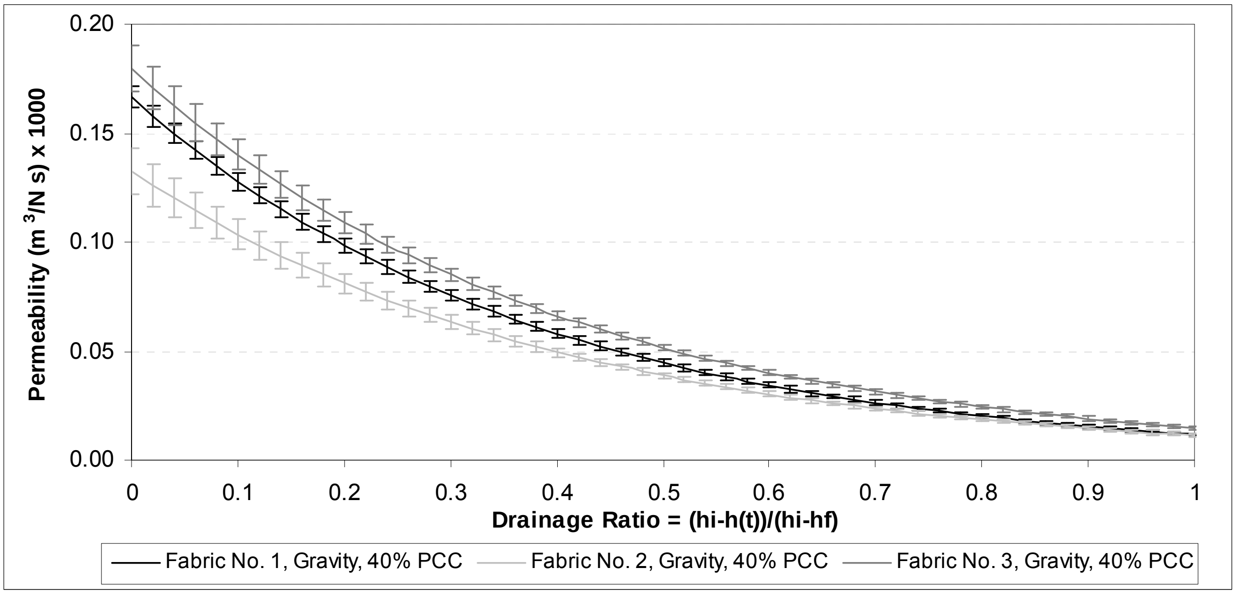

Figure 11: Permeability *versus* drainage ratio (gravity drainage)

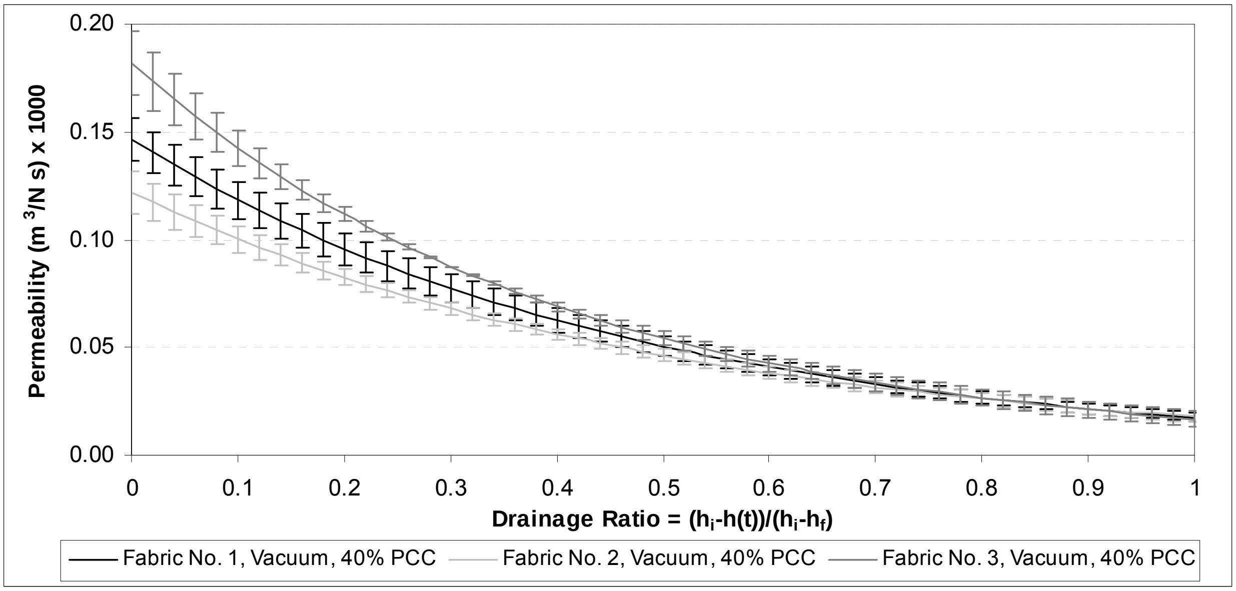

Figure 12: Permeability *versus* drainage ratio (vacuum drainage)

In both Figure 11 and Figure 12 there is a distinct difference in the permeability of the forming fabrics and fibre mats which is indicative of different levels of retention, especially of fines and filler. All of the fabrics tend to approximately the same permeability at the end of the sheet forming process, with slight differences due to variations in final basis weights. This observation shows that the permeability of the fabric and fibre mat is dominated by the fibre mat once a significant layer of fibres has been built up. This finding is consistent with previous experiments [42,43]. The permeability at the beginning of the experiments shows a much larger difference between the forming fabrics. This difference early in the forming process may be the cause of differences in overall retention. Until some fibre mat is built up, the exposed openings in the forming fabric surface are large enough to allow passage of fines, filler and poorly oriented fibres. As the pulp slurry drains, deposited fibres cover openings in the forming fabric and reduce the permeability of the forming fabric and fibre mat combination; increasing the instantaneous retention. Forming fabrics that have a higher initial permeability will have a lower initial retention and will retain less material throughout the process, particularly in the early stages of fibre mat build-up.

2.4 Conclusions

A modified hand sheet former was constructed to allow for comparison of overall retention results for hand sheet forming under an applied vacuum for different forming conditions. The variables tested were different forming fabrics, filler loadings, suction pressure and the presence of chemical retention aids. The presence of chemical retention aids was found to be the most significant factor affecting the overall retention. It was found that the overall retention shows a small dependence on applied suction pressure: an increase in suction pressure decreases the overall retention. The forming fabric selection was shown to have a statistically significant effect on the overall retention results even with basis weights of 40-50g/m^2. Increasing the filler loading in the initial pulp suspension increases the performance gap between forming fabrics and makes the fabric selection more significant in determining the overall retention. Further tests showed that the overall retention results under gravity drainage conditions showed good correlation with forming fabric air permeability values. Measurement of the instantaneous permeability of the forming fabrics and fibre mats during forming showed that the fabric properties are important in determining permeability in the initial forming stages but become less significant as a heavier fibre mat is formed. This initial difference in permeability may explain the difference in overall retention between fabrics.

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Chapter 3 - Filler Removal and Migration due to Applied Suction in Hand Sheet Forming[2]

3.1 Introduction

During paper forming the sheet constituents are not uniformly deposited throughout the z-direction. This two-sidedness leads to variations in paper properties that can negatively affect ink receptivity, surface strength and roughness, dusting, brightness, bending stiffness, etc. [1-3]. Though two-sidedness also refers to changes in sheet density and formation through the z-direction, the main reason for this heterogeneity of paper properties is the distribution of fines and filler material in the z-direction. It has been shown that the filler distribution in a sheet is also related to the total filler retention [4], which indirectly relates filler distribution to sheet properties that are typically associated with overall filler content – opacity, printing quality, drainage, retention, cost [5-8] – and further emphasizes the importance of filler distribution. The mechanisms by which the fibre mat acts to retain filler particles are electrostatic attraction (deposition), filtration, sedimentation, and flocculation. It has been reported that the primary mechanism for filler retention is deposition (or attachment) by chemical interaction (i.e., van der Waals electrostatic forces), and that the other mechanisms are of secondary importance [9,10].

The primary method for controlling filler distribution is the choice of paper machine. Each machine type has a filler distribution that is associated with the types of forming conditions produced in the pulp suspension. Formation of a standard hand sheet results in low filler concentration on the top side, increasing to a peak between the center and the wire side, and finally a slight decrease towards the wire side [2-4]. Formation on a Fourdrinier machine results in a non-symmetrical distribution with a trend of increasing concentration from wire side to top side [1,3,11,12]. The difference between the distribution in a hand sheet and paper formed on a Fourdrinier machine is due to pressure pulses and backwash from machine forming elements disturbing the wire side mat and removing filler particles [1]. On hybrid formers there is a reduction in top side filler content from that of a Fourdrinier machine. This is caused by the fraction (approximately 30-45%) of the dewatering that happens through the top of the sheet, resulting in a more symmetrical filler concentration profile with a peak near the center of the

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[2] A version of this chapter will be submitted for publication. Montgomery, J., Green, S.I., Vaberek, A., and Jong, J., (2010) Filler Removal and Migration due to Applied Suction in Hand Sheet Forming.

sheet [3,12,13]. Twin-wire forming is characterized by a symmetrical filler distribution, the shape of which depends on the applied drainage elements and furnish used [3,12].

Early investigations on hand sheet and Fourdrinier forming determined that the filler distribution in the final sheet was dependent on basis weight, dandy rolls and the forming type [1,2]. These same studies found that the suspension consistency did not affect the distribution if it was maintained within practical papermaking limits. Large changes in consistency, however, were found to change the filler profile. Tests to determine the effects of suction and pressing on filler distribution during hand sheet [1,4] and Fourdrinier [2] forming found that there was none. From these observations it was concluded that the filler profile is fixed (at the dry line) on the paper machine.

The bulk of more recent work regarding filler distribution has focused on layering principles [3,11-17]. A multilayer headbox is used with a gap former to allow for separation and layering of pulp furnish, fillers, and additives to control distribution throughout the sheet. The main outcome of these studies was to show that the filler distribution can be controlled by layering retention aids [12-15]. The use of loadable drainage elements was also tested and showed that filler distribution could be changed by increasing the dewatering through blade elements [11,13,15], suction rolls [11] and suction shoes [12,13]. These studies stated that the type of change in filler distribution was dependent on furnish and showed inconsistent findings with relation to increased dewatering and the changes in profile as well as total filler content.

A detailed study into the effect of wet pressing on filler distribution was conducted by Szikla and Paulapuro [18]. They found that under normal pressing conditions the filler will exit with water but not change the distribution. Conclusions drawn from pressing results highlighted a number of factors that affect filler distribution; flow velocity, filler content, particle size, and pulp furnish.

A number of studies have focused on passing a suspension of filler through a pre-formed pulp mat [19-21], to determine the viability for filling mass-produced paper [22]. These studies show that migration of filler particles through a fibre network is possible but did not investigate the degree of migration or how the migration occurs.

The previous studies investigating applied suction on filler particles did not occur under tightly controlled conditions and inconsistent results were obtained. There has also been no work to investigate the migration of filler particles within a sheet and to determine the relative effects of suction on filler content. In section 2 we describe a modified hand sheet former that allows for the testing of the effects of applied suction (wet and dry), filler type, and suspension consistency on filler distribution in a hand sheet. Section 3 presents results related to filler distribution and the migration of filler particles within a sheet. The paper closes with conclusions and recommendations for future work.

3.2 Apparatus, Materials and Method

All hand sheets were formed in a custom device that has some similarities to a standard hand sheet former. Figure 13 shows a schematic of the apparatus. The apparatus is constructed of a 3” (75mm) diameter, 6” (150mm) high, clear acrylic circular cylinder below a forming fabric. A flush-mounted gauge pressure transducer (GP:50 Model 218-C-SZ-10-GS) is mounted in the wall of the test chamber below the forming fabric. As described below, the pulp slurry above the forming fabric is exposed to the atmosphere, so the pressure transducer measures the pressure drop across the forming fabric and fibre mat. Another circular cylinder is attached above the forming fabric and a gasket is placed around the outside to provide an airtight seal. A vacuum chamber constructed of ½” (13mm) thick PVC sheets is connected to the bottom of the test chamber by a ¾” (20mm) PVC pipe and electrically actuated solenoid valve. The vacuum chamber can be adjusted to the desired pressure by an attached vacuum pump.

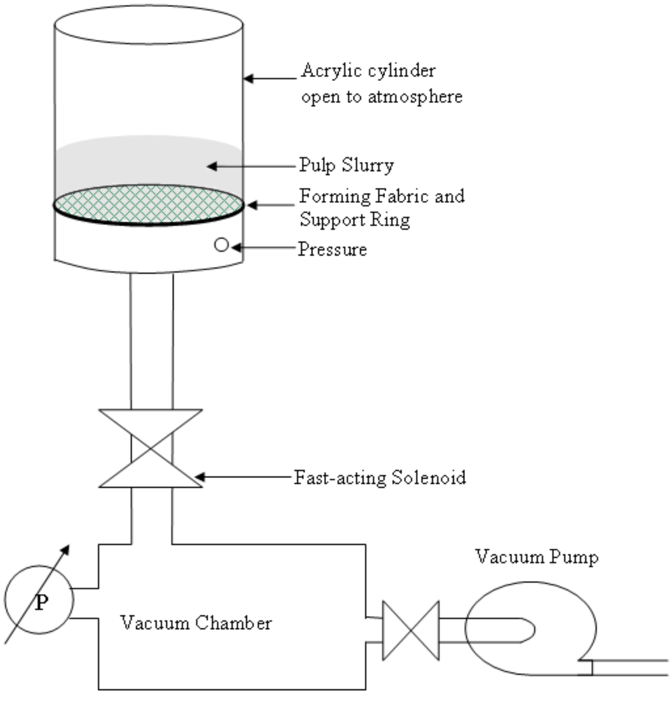

Figure 13: Schematic of modified hand sheet former

Pulp slurry at 0.5% consistency with the appropriate filler type was prepared by dispersing 40g of fibre and filler into 1600mL of 80°C distilled water. The slurry was mixed for 7.5min at 3000rpm and then diluted to 0.5% consistency with additional distilled water. The slurry was refrigerated until use, at which point it was continuously stirred by a laboratory mixer at 250rpm throughout the experiment. To determine the error associated with sampling from this stirred slurry, multiple equal-volume samples were taken from the slurry. The different samples were then filtered through 0.5μm filter paper and the variation in dried mat weight was measured. This procedure was measured to provide a uniformly dispersed mixture with a sampling variation of less than 1%.

To form a hand sheet, distilled water is added to the apparatus between the (closed) valve and the forming fabric. A sample of pulp slurry is measured and transferred into the top cylinder above the forming fabric. The quantity of pulp suspension is varied depending on the forming conditions to provide a final sheet basis weight of 60g/m^2. A Labview program is used to start the experiment by opening the solenoid valve, exposing the test chamber and pulp suspension to the vacuum pressure. The water in the test chamber drains into the vacuum chamber and a fibre mat is formed on the forming fabric. During dewatering the pressure drop across the forming fabric and fibre mat is recorded. The voltage signal is filtered using a low pass filter and written to a file for later analysis. Upon test completion the solenoid valve closes automatically. The fibre mat is removed and oven dried.

Hand sheets were formed using pulp suspensions containing 40% filler. The pulp used was a softwood, hydrogen peroxide bleached, thermo-mechanical pulp (post latency removal, 30% fines) at 0.5% consistency. Two filler types were tested. The first filler was Albacar HO (Specialty Minerals Inc.) dispersed in distilled water; a cationic (+0.1μeq/g), scalenohedral precipitated calcium carbonate (PCC, $CaCO_3$) with a volume-weighted mean particle size of 5.4μm. The second filler used was anionic (-1.7μeq/g) ground clay ($Al_2Si_2O_5(OH)_6$), a platelet shaped filler, with a volume-weighted mean particle size of 10.8μm. Particle sizes and distributions were determined using a Mastersizer 2000 (Malvern Instruments Ltd.). Though the two filler types have different particle sizes they are both smaller than typical mat pore sizes and so filler size is unlikely to play a large role in retention results [23]. The hand sheets were all formed on the same triple layer forming fabric provided by AstenJohnson (Kanata, Canada). Hand sheets were formed with one or both filler types under gravity drainage, vacuum drainage, and gravity drainage with a subsequent vacuum pulse applied to draw air through the wet fibre mat. A limited number of tests were performed using chemical retention aids using the pulp suspension containing PCC filler. With these sheets it was possible to determine the effect of applied suction pressure on the z-direction filler distribution and migration for two filler types in a hand sheet.

Hand sheets that were used to test both filler types simultaneously were formed in two parts. The lower half of the sheet was formed first as described above. The forming fabric and adhering wet pulp mat is removed from the apparatus and the lower chamber refilled with distilled water. The fabric and mat are replaced in the test chamber and the upper portion secured. A 14 mesh screen is then placed on top of the pulp mat to prevent motion of the pulp fibres when the top pulp suspension was added. The suspension for the upper portion of the sheet is added without disturbing the lower pulp mat. The solenoid valve is re-activated to drain the top portion of the suspension. The pulp mat is removed from the apparatus, split into the upper and lower portions, and oven dried. The mass of pulp suspension used for the upper and lower portions of the sheet is calibrated to provide a final basis weight of 30g/m^2 in each half.

Z-direction filler distribution was determined by two methods. Both methods first split the dried sheet into multiple layers of approximately equal weight using adhesive tape. For the sheets formed using only one filler the layers of sheets were weighed, ashed and the remaining mineral content weighed to provide the percent filler in each sheet layer [20]. The ashing method was not appropriate for sheets with two filler types and so energy dispersion X-ray (EDX) was used to determine the amount of mineral in each layer. The EDX analysis method used was a modification of that introduced by Modgi et al. [25,26] that analyses the surface of split sheet layers rather than the cross section of a cut sheet. The PCC is represented in EDX results by weight percent calcium (Ca) and the clay by aluminum and silicon (Al and Si) because these are elements unique to the filler particles. Note that because each filler is comprised of more elements than simply Ca or Al and Si, the absolute magnitude of filler weight percentages computed in this way is too low, but the relative weight percentages in the Z-direction are not affected by this bias. The actually filler content is determined by stoichiometric conversion.

3.3 Results and Discussion

3.3.1 Z-Directional Filler Distribution

Z-direction filler profiles for 60g/m^2 hand sheets formed using pulp suspension containing 40% PCC filler are shown in Figure 14. The curves represent drainage under gravity and vacuum (vacuum chamber set to -50kPa). The profiles were determined by sheet splitting and ashing. Each step in the graph is the average ash content achieved by ashing from five different hand sheets. A comparison of the average filler content of the sheets clearly shows that applying a vacuum during the drainage process reduces the amount of filler retained. This finding is consistent with our previous study of retention [27]. It is evident from the filler distribution curves that the applied vacuum also changes the filler distribution. The majority of this filler reduction occurs on the wire side with the top side remaining essentially unchanged.

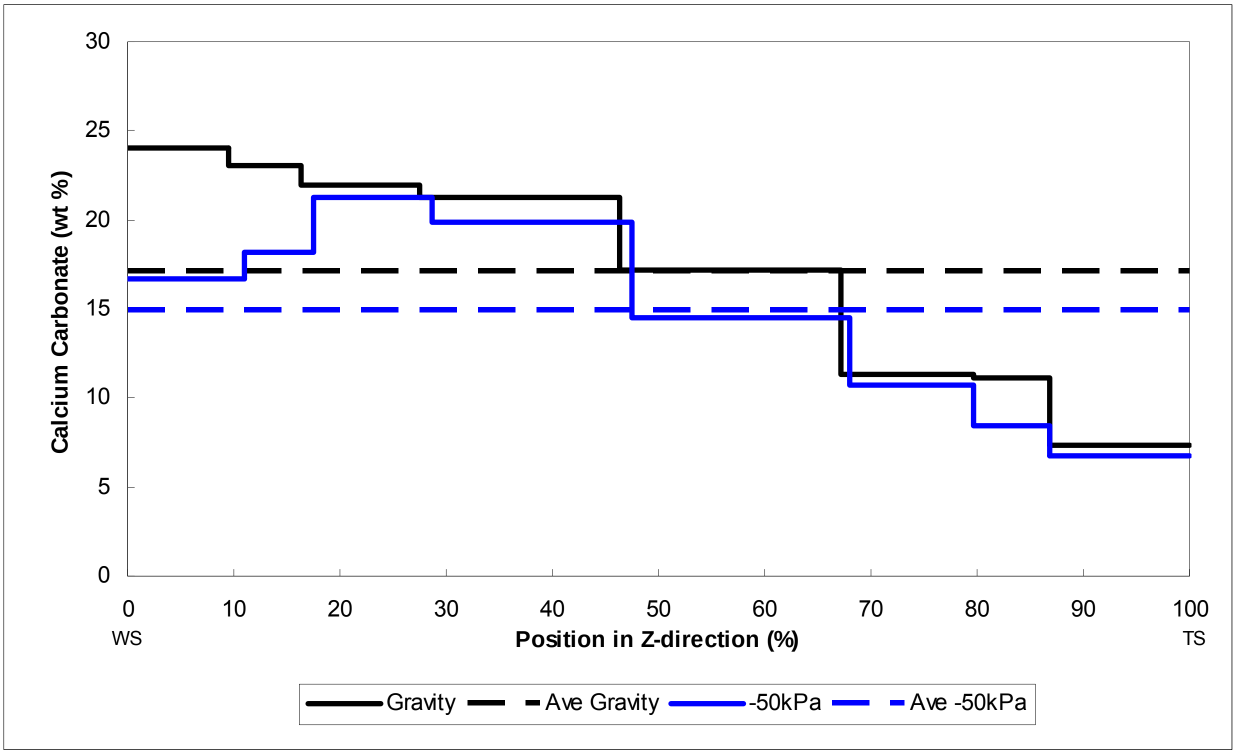

Figure 14: Distribution of PCC in hand sheets formed with pulp suspension containing 40% cationic PCC filler under gravity and vacuum drainage determined by ashing

The effect of applied suction on filler distribution was also tested on hand sheets formed with chemical retention aids. These results are not shown in any figures in this paper. Sheet splitting and ashing showed a constant distribution of filler throughout the sheet and no change due to applied suction. Tanaka [4] previously reported that an increase in chemical retention aids beyond a certain limit would result in an even filler distribution throughout the sheet. The absence of change in distribution when vacuum was applied during drainage with retention aids could be explained by the increase in agglomerate size. The volume weighted mean PCC particle size is 5.4µm without chemical retention aids and 18.1µm with chemical retention aids. The increased size of filler agglomerate increases the probability of filtration retention. This along with the increased electrostatic attraction due to the charge modification from the retention aids could overcome the increased drag due to vacuum and result in markedly decreased filler mobility.

Figure 15 shows z-direction filler profiles for 60g/m^2 hand sheets formed using pulp suspension containing 40% PCC filler. The curves represent drainage under gravity, gravity with a subsequent vacuum pulse (dry vac), and gravity drainage with a greatly reduced consistency (0.02%C). The profiles were determined by sheet splitting and ashing. Each step in the graph is the average ash content achieved by ashing from five different hand sheets. The results for filler distribution for gravity drainage with a subsequent vacuum pulse show no substantial change from the distribution achieved with gravity drainage alone. This would imply that after the initial gravity drainage the filler particles are fixed in the fibre mat.

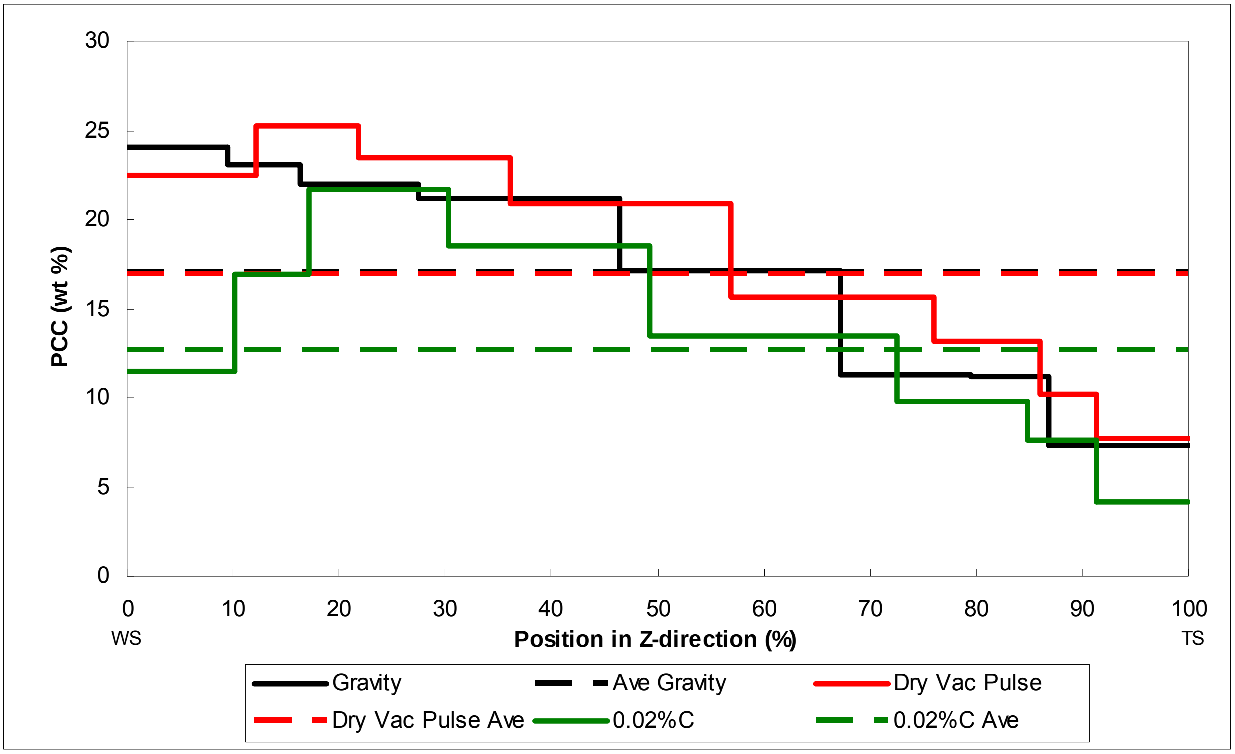

Figure 15: Distribution of PCC in hand sheets formed with pulp suspension containing 40% cationic PCC filler under gravity drainage, gravity at 0.02%C and gravity with a subsequent dry vacuum pulse determined by ashing

The shape of the filler distribution curve for gravity drainage found using the modified hand sheet former and pulp suspension containing 40% PCC filler is different from that of the standard hand sheet distribution. Previous researchers [1,4] have stated that the filler distribution in a hand sheet is not affected by applying a vacuum during drainage, which is contrary to the results found here. These differences may be due to the forming apparatus, the large difference in consistency between the studies, or the different filler types used.

It has previously been concluded that large changes in consistency will change the filler distribution in paper [2]. The filler distribution of hand sheets formed using a 0.02% consistency in Figure 15 shows obvious variations from those formed with 0.5% consistency. The lower consistency shows the ‘typical’ hand sheet filler distribution of an increase from top side to past center with a subsequent decrease towards the wire side. The average filler content throughout the sheet is also reduced. From these results it is clear that the consistency difference is one reason for the different filler distributions realized in Figure 15 of this study (0.5%C) and previous works (0.02%C) investigating filler distribution in hand sheets.

Ashing of hand sheets is a time intensive process that cannot distinguish between filler types. Filler distribution can also be determined by sheet splitting and EDX analysis. Before performing analysis on filler migration using EDX and sheets formed by the two suspensions (as described in section 2) it was required to determine if any error was introduced due to the forming or analysis method. Figure 16 compares filler profiles determined using EDX for gravity and vacuum drainage from sheets formed as two 30g/m^2 layers separated by a screen for cationic PCC with those of the ashing methods used above. The EDX analysis provides the weight percentage of elements only and therefore the CaCO3 content was determined by stoichiometric conversion. The similarity in z-direction filler distribution between the two analysis methods shows that the forming and analysis techniques do not introduce significant error and are suitable for experimental comparison.

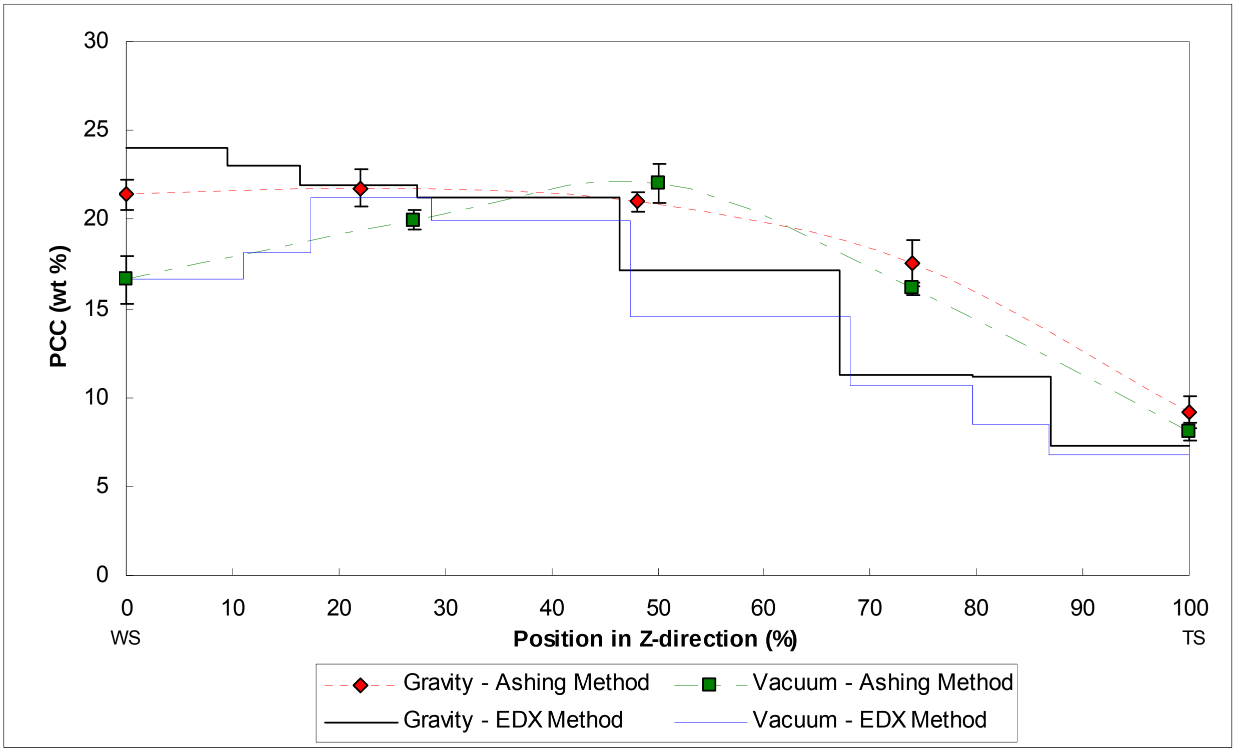

Figure 16: Comparison of PCC distribution in hand sheets determined using EDX and ashing methods

The typical z-directional filler distribution from previous studies was obtained using clay as filler. Clay filler is anionic whereas the PCC used in Figures 2, 3, and 4 is cationic. This charge difference is likely to result in different total retention [28] and z-direction filler profiles. Figure 17 shows the z-direction filler distribution for hand sheets formed to 60g/m^2 under both gravity and vacuum drainage determined using EDX analysis. The error bars represent the standard error. Hand sheets made of pulp suspensions containing cationic PCC show higher filler retention than those containing anionic clay filler. The difference in filler content between PCC and clay is caused by the different retention properties of the filler types. The filler distribution in hand sheets formed with clay filler show the 'typical' trend of increasing filler from top side to past centre with a subsequent decrease in filler content towards the wire side, which is different for the filler trends in paper with PCC filler. This finding shows that the filler type used, specifically its charge relative to pulp fibres, affects the z-direction filler distribution. Filler that has an electrostatic repulsion to pulp fibres (clay) shows a decrease in concentration near the wire side under gravity drainage. Filler that has an electrostatic attraction to pulp fibres (PCC) shows a plateau at the wire side under gravity drainage. The two filler types also react differently to an applied vacuum during drainage. The cationic PCC shows a reduction of filler on the wire side when vacuum is applied. The anionic clay shows no change.

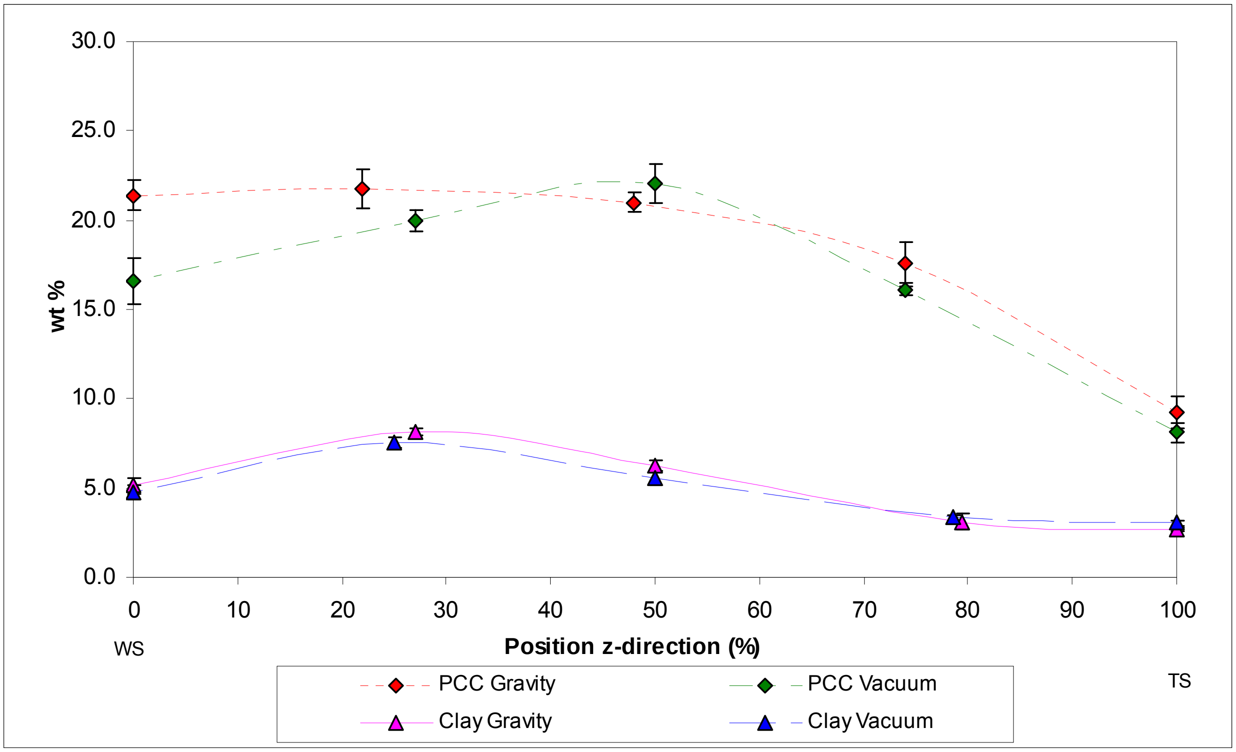

Figure 17: PCC and clay distribution in hand sheets determined using EDX analysis

3.3.2 Z-Directional Filler Migration

It is desirable to understand the role that filler in the top layers of the pulp suspension plays in filling the lower portion of the sheet and how this migration is affected by the application of a vacuum during drainage. Figure 18 shows total PCC distribution in hand sheets as well as the filler profiles in the sheet that are representative of filler from the upper and lower portion of the pulp suspension. The total filler curves were determined by EDX analysis of a 60g/m^2 sheet. The distribution from the filler in the lower half of the pulp suspension was determine by forming a 30g/m^2 hand sheet. The distribution from PCC in the upper portion of the sheet was determined by subtracting the filler content of the 30g/m^2 sheet from the 60g/m^2 sheet at each location. The two curves for filler from the lower portion of the pulp suspension (triangle symbol) show that very little filler is retained in the early stages of the forming process. Applying vacuum during the early forming slightly reduces the filler content at the wire side. The filler from the upper half of the pulp suspension (square symbol) shows an increase from top side to center and then a subsequent decrease at the wire side. Retention of filler in the upper portion is far greater than in the initial stages of forming. This is caused by the added resistance of the fibre mat in the lower portion of the sheet. As the filler in the upper pulp suspension flows through the pulp mat deposited in the early stages of forming by the lower portion of the suspension, some of the filler particles are filtered, which greatly increases the retention. The total PCC distribution (diamond symbol) shows the same differences in filler distribution for gravity and vacuum drainage as described earlier.

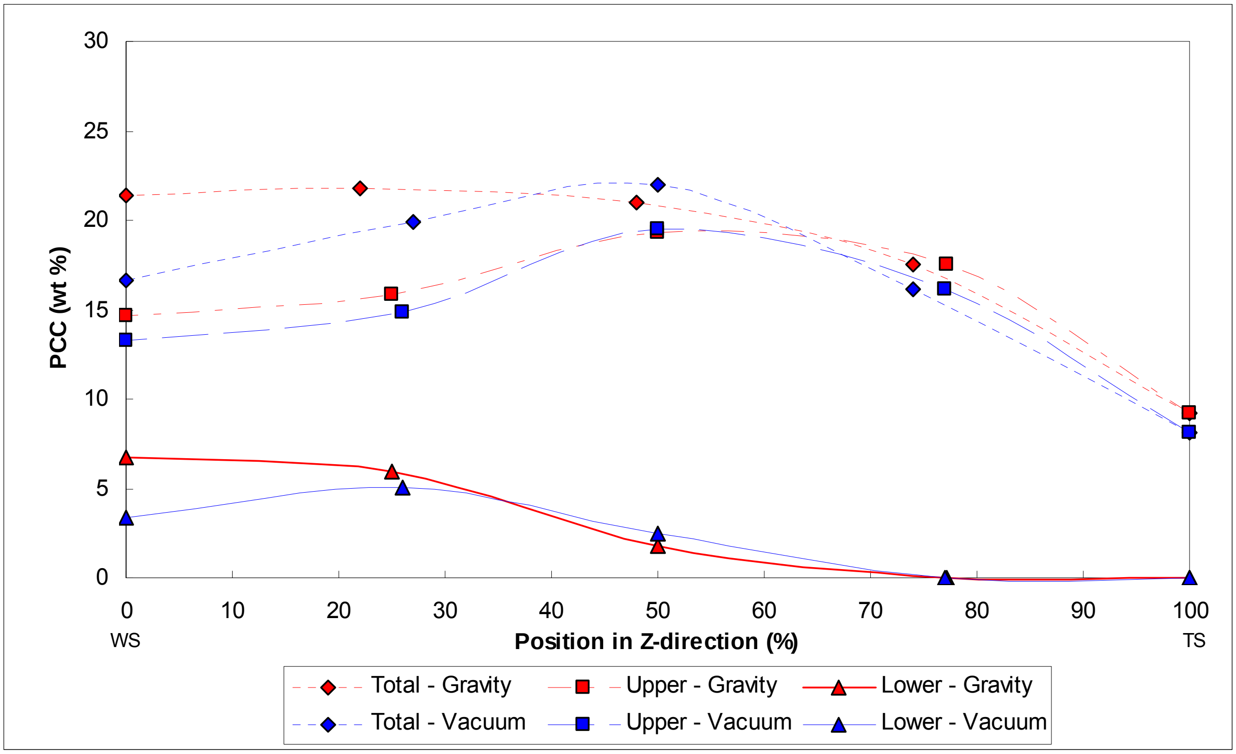

Figure 18: PCC distribution in hand sheets divided into profiles from filler in upper and lower portions of a pulp suspension

An understanding of how different filler types migrate in a hand sheet depending on where in the pulp suspension they occur can be determined by forming a 60g/m^2 hand sheet in two parts, as described in section 2. The filler (clay and PCC) can be tested in both the upper and lower portion of the hand sheet to determine if there are differences in the ways that different filler types fill a hand sheet. It is also possible that an understanding of the reasons for different filler profiles can be determined based on different retention and migration patterns illuminated from forming sheets in this manner.

3.3.2.1 PCC in Lower Pulp Suspension, Clay in Upper Pulp Suspension

The hand sheets were formed with a lower pulp suspension containing PCC filler and an upper pulp suspension containing clay filler. Figure 19 shows the z-direction distributions of the total filler, PCC, and clay for hand sheets formed using gravity and vacuum drainage. Each data point is the average filler content determined from at least three locations (relative to the fabric yarn pattern) on sheet splits from three hand sheets formed under identical conditions. The filler content is determined by EDX analysis on sheet layers and stoichiometric conversion. The error bars show the standard error of the results.

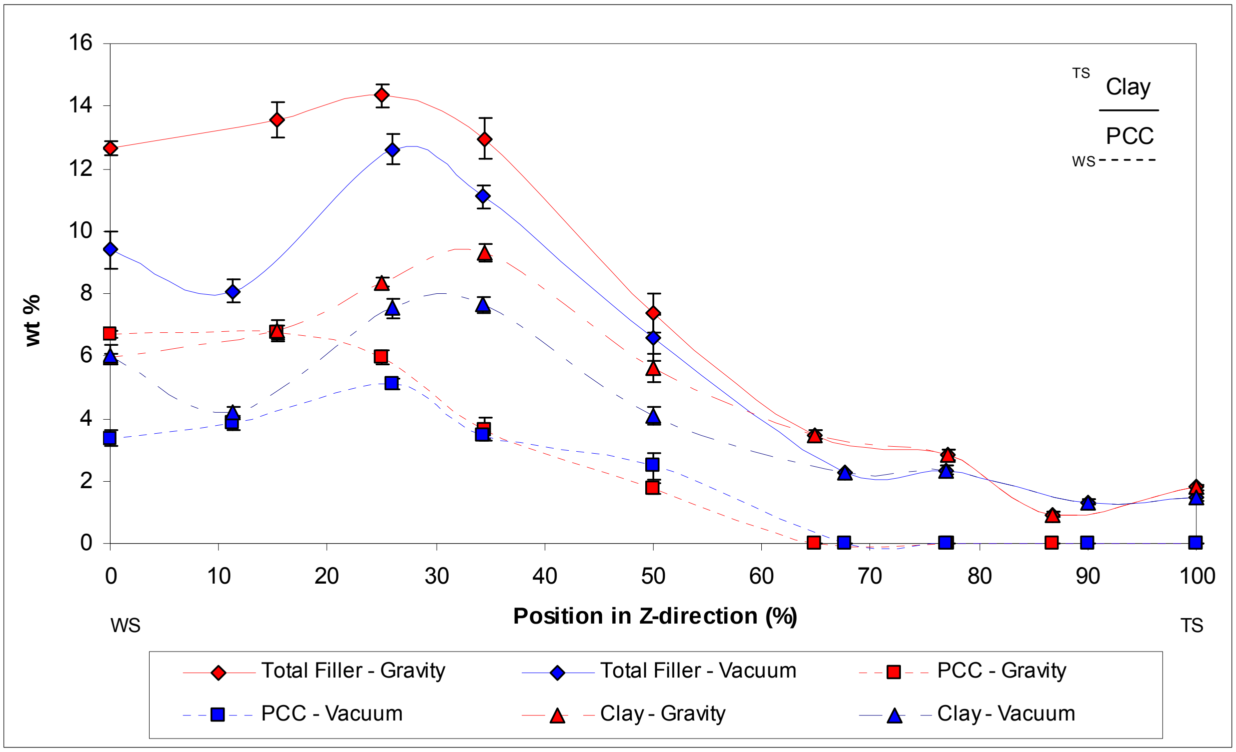

Figure 19: Breakdown of filler distribution in sheets formed with PCC pulp suspension on the lower half and clay pulp suspension on the upper half

The total filler content (diamond symbols) in the sheets formed in this manner shows no change in the trends seen when sheets are formed using only PCC filler. Under gravity drainage the total filler content shows an increase from top side to wire side until a plateau is reached. Applying a vacuum during drainage causes a reduction of the overall filler content. The majority of the reduction occurs on the wire side of the sheet with little change in filler content in the top half.

Analysis of the individual filler types provides information on the different characteristics of retention for filler from the upper half and the lower half of the pulp suspension. The PCC content (square symbols) from the lower suspension shows an increase from the middle of the sheet to the wire side. The higher filler content in the lower layers suggests that as the pulp mat forms it is filtering out filler from the suspension that passes through it and not only retaining filler by attachment to fibres. It is speculated that the PCC content shows a reduction at the wire side when vacuum is applied because of the increased flow rate. The increased flow rate is highest at the wire side of the sheet because the wire side has the highest resistance [11] and thus the lowest effective open area. The change in filler profile is a result of filler particles that would remain attached to fibres during gravity dewatering being removed due to higher drag forces in vacuum dewatering. The retention of clay (triangle symbols) in the upper portion of the sheet is very low. There is a marked increase at the center of the sheet and then a decrease towards the wire side. The poor retention in the upper portion of the sheet can be attributed to the repulsive forces between the clay and pulp fibres. Clay particles are filtered as the upper suspension drains through the fibre mat in the lower half, which causes the retention to increase, except for very near the wire side. Applying a vacuum during drainage only slightly reduces the clay content throughout the sheet. This reduction could be attributed to the increased flow rate causing less retention by filtration. Figure 20 is a simplified diagram of the different effects that an applied vacuum has on particles retained by attachment and filtration.

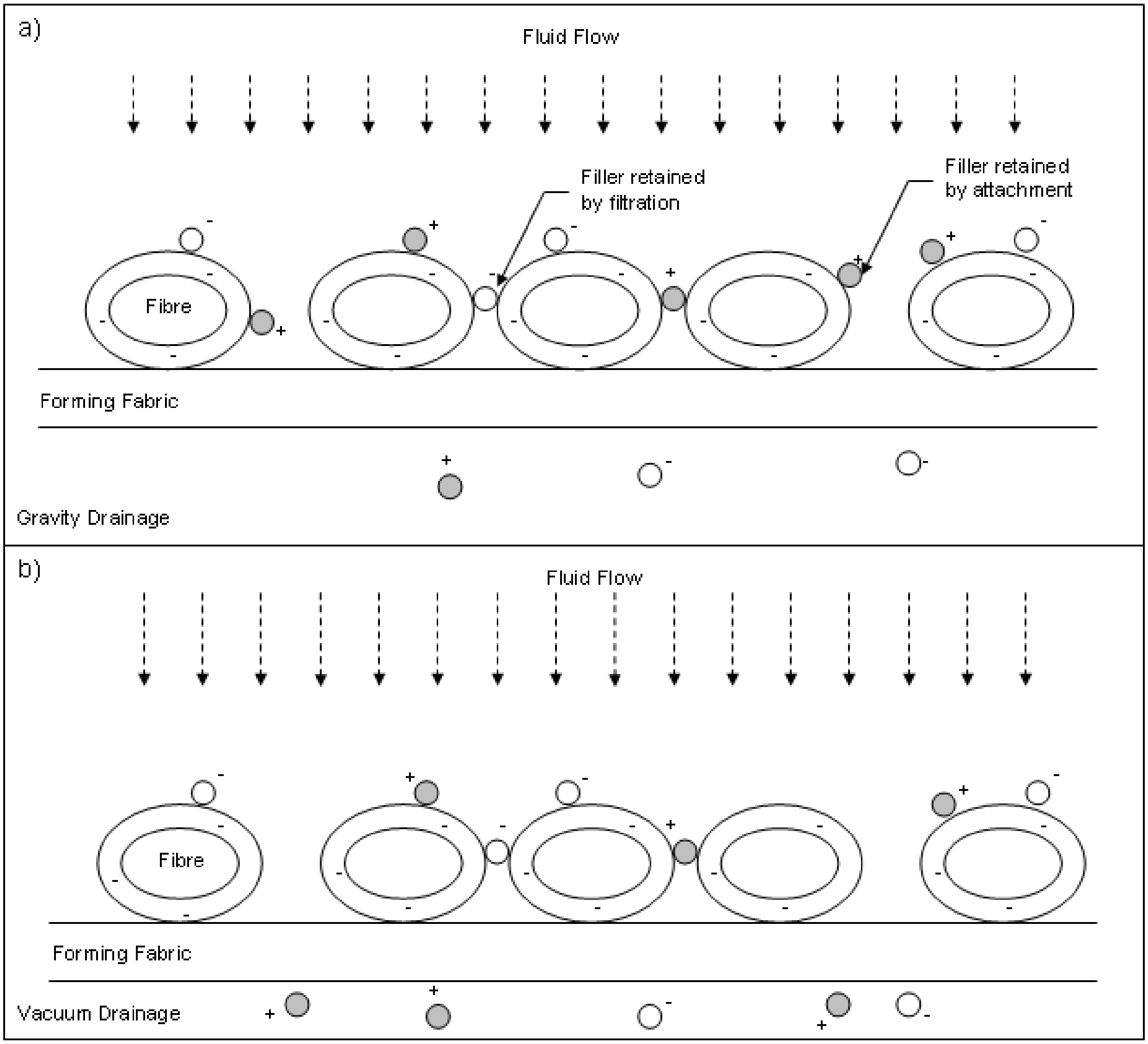

Figure 20: Effects of gravity (a) and vacuum (b) on filler retained by attachment and filtration

3.3.2.2 Clay in Lower Pulp Suspension, PCC in Upper Pulp Suspension

Additional hand sheets were formed with a lower pulp suspension containing clay filler and an upper pulp suspension containing PCC filler. Figure 21 shows the z-direction distribution of the total filler, PCC, and clay formed using gravity and vacuum drainage. Each data point is the average filler content determined from at least three locations (relative to the fabric yarn pattern) on each of three different hand sheets formed under identical conditions using sheet splitting. The filler content is determined by EDX analysis on sheet layers and stoichiometric conversion. The error bars show the standard error of the results.

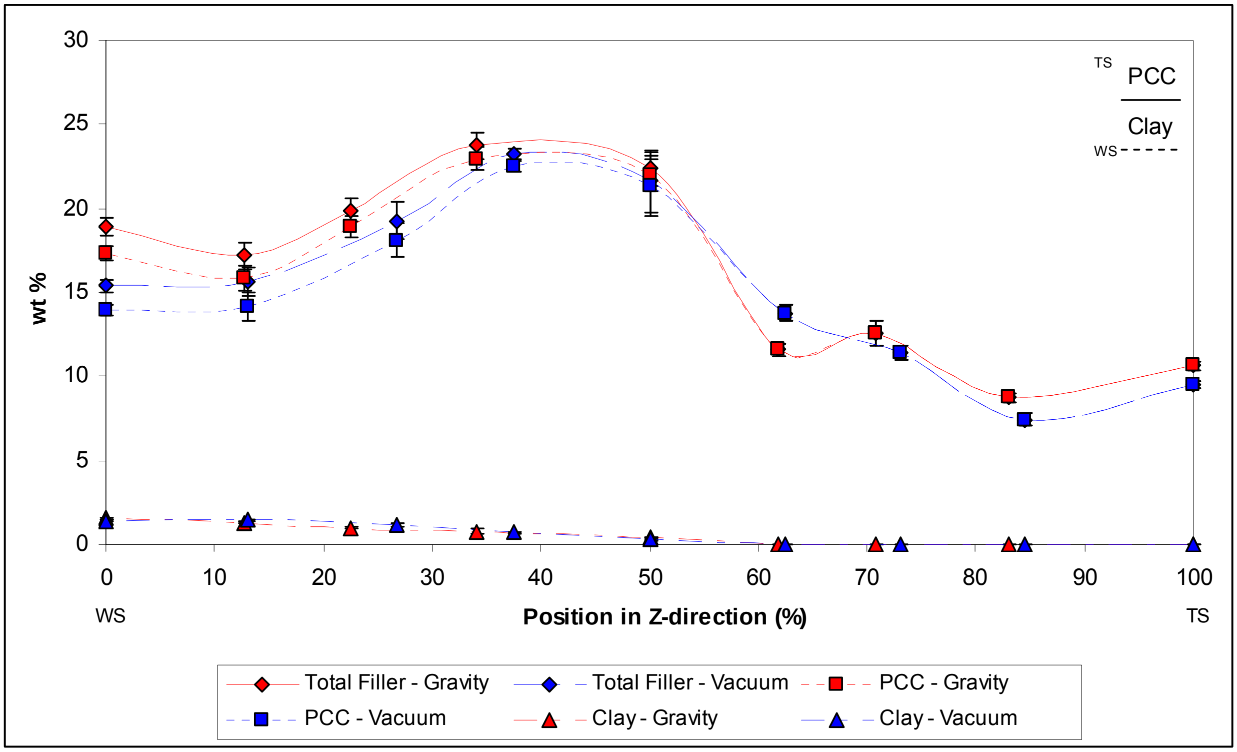

Figure 21: Breakdown of filler distribution in sheets formed with clay pulp suspension on the lower half and PCC pulp suspension on the upper half

The average total filler content (diamond symbols) in the sheets formed in this manner is significantly higher than those formed with the pulp suspensions in reverse order. The reason for this is the greater retention of PCC (square symbols) when in the upper suspension because of the additive effects of attachment and filtration retention. Figure 21 shows that the total filler distribution in the sheets is dominated by the PCC distribution. The total filler content of hand sheets formed in this manner shows a smaller reduction when vacuum is applied during drainage compared with hand sheets formed with PCC in the lower suspension and clay in the upper suspension (Figure 19). This may also be due to the PCC having higher retention properties when in the upper suspension due to increased filtration retention.

The filler distribution profiles for clay (triangle symbols) in Figure 21 show that there is very little retention of clay particles. Since clay particles and pulp fibres are both anionic, the vast majority of clay retention is from filtration, which is difficult to achieve in the early stages of sheet forming because of the limited fibre mat. This observation is consistent with the increasing clay content from the center of the sheet to the wire side. The layers of the fibre mat deposited first will have more filler passing through them in suspension and a greater probability of filtering particles. The low clay retention in the lower portion of the sheet prevents the profile of overall filler content from reaching the plateau seen for gravity drainage with only PCC in Figure 17 and gravity drainage with the reverse filler layering (Figure 19). This suggests that migration of filler from the upper portion of the pulp suspension cannot compensate for poor initial filler retention during the forming of the pulp mat at the wire side. When vacuum is applied during the forming of the top layer of the sheet there is no discernible difference in the content or profile of clay; clay particles that are already retained in the fibre mat by filtration are not susceptible to the negative effects of increased flow rate due to the application of vacuum. The application of vacuum also does not pull additional PCC from the upper layers when compared with gravity drainage. This is further evidence that the application of vacuum at later stages in the forming process cannot compensate for poor initial filler retention on the wire side. These findings show that it is important to ensure high initial filler retention for high wire side filler content in paper manufacturing.

3.3.2.3 Influence of Upper Suspension Filler

A comparison of clay in Figure 19 and PCC in Figure 21 provides information of the retention of the filler particles in the top portion of a pulp suspension during drainage. Both the PCC and clay exhibit filler distributions similar to that shown from standard hand sheet forming. The filler content increases from the top side towards the wire side, peaking after the center and slightly decreasing towards the wire side. There is considerably higher retention of both filler types when the filler is in the upper portion of the pulp suspension. Applied vacuum during drainage has only a small effect on the retention. These observations can both be explained by the filtration retention of particles in the upper suspension. Clay particles are only retained by filtration in the pulp mat and PCC particles are retained by both filtration and attachment. This would imply that filler retained by filtration is not affected by applied vacuum to the same extent as filler retained by attachment.

3.3.2.4 Influence of Lower Suspension Filler

A comparison of PCC in Figure 19 and clay in Figure 21 provides information of the retention of the filler particles in the bottom portion of a pulp suspension during drainage. Both fillers have a lower retention than when used in the upper suspension. This is because of the low probability of filtration retention in the early stages of sheet forming. It is interesting to note that the PCC in the lower portion of the sheet exhibits a dip in retention at the wire side when vacuum is applied but clay retention remains unchanged. The clay retention is also significantly lower than the PCC retention or clay retention in the upper suspension. The cause of both the low retention and the negligible reduction when vacuum is applied is that clay particles are retained almost exclusively by filtration. PCC is retained by filtration and attachment to pulp fibres. This finding is further evidence that filtration retention has only a small dependence on applied vacuum.

3.4 Conclusions

A modified hand sheet former was used to compare the affects of applied vacuum on filler distribution and migration in sheet forming at approximately headbox consistency (0.5%). The variables tested were vacuum pressure, filler type, consistency, and retention aids. Hand sheets formed with cationic PCC filler showed a different filler profile than those formed using clay filler. At the wire side of a sheet, PCC shows a plateau at maximum filler loading whereas clay filler content decreases. This is attributed to the low retention of clay in the initial stages of hand sheet forming. Vacuum applied during drainage was found to affect the filler distribution of hand sheets made with PCC but not that of hand sheets with clay filler. The clay filler is retained by filtration and so is trapped in the fibre web even when greater drag forces are applied. The overall PCC content of the sheet was lower when suction was applied during forming. The majority of the filler was removed from the wire side. The application of vacuum, after the pulp mat has undergone initial gravity drainage, does not change the filler content or distribution. This vacuum pulls air through the mat, removing water in which only very small filler particles are still entrained and so no appreciable change in filler distribution or content is seen. Sheet forming using PCC at a greatly reduced consistency (0.02%) showed the ‘typical’ filler profile similar to forming with clay.

As the pulp mat builds up during drainage some filler particles are retained by filtration. The amount and profile of particles retained by filtration are only slightly affected by applied vacuum during the forming process. This can be explained by the compaction of the pulp mat. When a vacuum is applied the fibre mat is compacted, with the greatest compaction near the wire side. As the mat compacts there is a reduction in the effective area. Even though this reduction in area speeds up the local flow velocity, producing a higher drag, the reduced area makes it harder to remove particles that are trapped by filtration, which tend to be larger than the openings in the fibre network.

Filler particles with a cationic charge will be attracted to the anionic pulp fibres resulting in retention by attachment. The amount and Z-direction profile of particles retained by attachment are largely affected by applied vacuum during the forming process. This can be explained by the compaction of the pulp mat and reduction in effective area as described above as well as the increase in bulk flow velocity due to suction. Particles that are retained by attachment are typically smaller than the openings in the fibre network and are retained primarily by electrostatic forces between the filler particle and adjacent pulp fibres. When suction is applied during forming the bulk velocity is increased which causes an increase in drag on the particles. Filler can be removed from the pulp fibres if the drag force exceeds the electrostatic attraction. Compaction of the pulp mat occurs to the greatest extent at the wire side. Therefore the local velocity, and drag on filler particles, will have the greatest increase in this area, causing a greater reduction in filler retention due to attachment to fibres.

Forming a hand sheet in two stages, using a single filler type or two different filler types, clearly shows that filler migrates during the forming process. As the pulp mat builds up during forming the resistance to flow, and likelihood of filler retention, increases. Filler in the upper portion of the pulp suspension would have to pass through a greater amount of pulp mat to reach the wire, which increases the probability of retention. The majority of the filler retained in a hand sheet is from the upper portion of the pulp suspension. The majority of filler from the lower portion of the suspension is lost before a sufficient fibre mat can be deposited on the forming fabric. When initial filler retention is too low the filler in the upper pulp suspension cannot migrate through the sheet enough to compensate, resulting in lower wire side filler content. It is important during sheet forming to have high initial filler retention at the wire side to ensure high surface filler content. This has a practical significance when a multilayer headbox is used. For high surface filler content it is important to use a filler type with high initial retention, possibly through the use of retention aids, at the wire side and rely on larger, cheaper filler particles to be retained by filtration retention in the center layers.

Future experiments would shed light on the effect of different parameters on filler distribution and migration. Using retention aids throughout the pulp suspension was shown to result in an even filler distribution throughout the sheet. Given the increased interest in additive layering it would be beneficial to understand the effects of using retention aids in only the lower portion of the hand sheet. It would also be of interest to use chemical retention aids (such as PEI or aPAM) on the filler particles to reverse the charges. This would give insight into how particle shape changes filler distribution and migration trends.

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Chapter 4 - Conclusions, Contribution to Knowledge and Recommendations for Future Work

4.1 Conclusions

A modified hand sheet forming apparatus was constructed to allow for laboratory scale studies of the effects of forming under suction on hand sheets. The main focus was to determine the affect of suction boxes on overall retention, filler retention, and filler distribution and migration. The apparatus allowed for testing under conditions close to those seen in real paper forming such as suction pressures up to -60kPa, high suspension consistencies, chemical retention aid use, and fibre mat formation. The apparatus also allows for further studies to be performed to extend understanding of the affects that suction has in papermaking.

4.1.1 Overall Retention in Hand Sheet Forming

The modified hand sheet former was used to test various forming parameters and determine the affect on overall retention in hand sheet forming. Through the formation of a series of hand sheets it was possible to test different forming fabrics, filler loadings, suction pressure, and the presence of chemical retention aids.

Of all parameters tested it was found that the presence of chemical retention aids during sheet forming has the greatest affect on overall retention. A comparison of overall retention results for hand sheets formed with and without chemical retention aids using pulp suspensions containing 20% and 40% PCC filler was performed in Section 2.3.1. In all cases the use of chemical retention aids increases the overall retention. The effects are largest when a pulp suspension containing 40% filler is used. For a suspension containing 40% filler the overall retention increases from approximately 55% to 75%. For a suspension containing 20% filler the overall retention increases from approximately 70% to 78%. This dominance of retention aids in determining overall retention results is in agreement with previous studies stating that filler is predominantly retained by electrostatic attraction to pulp fibres [1,2]. The reason for the increased retention when chemical retention aids are used is fibre-filler and filler-filler electrostatic interaction. The increased attraction between fibres and filler promotes attachment to pulp fibres, increasing retention. The filler-filler attraction increases the size of filler particles by forming aggregates. In the experiments performed with PCC in the studies of Chapters 2 and 3 the volume averaged mean filler particle size increases by approximately 3.5 times, from 5.4μm to 18.1μm, when chemical retention aids were used. The increased size of filler particles causes a large increase in the probability of filtration retention which is not seen in retention studies that make use of a dynamic drainage jar [3-10], preventing mat formation. A theoretical investigation of filler retention performed by van de Ven [11] concluded that increases in filler size or decreases in mat pore size can drastically increase filler retention. From that order of magnitude investigation, and the experimental results obtained here, it is clear that for certain combinations of increased mat resistance and/or filler size, filtration resistance, and thus mat formation, becomes an important factor in the retention of filler particles, especially in light of the industries trend to further increasing filler content.

It was found that there is a linear relationship between applied suction during forming and the overall retention in a hand sheet. There is a decrease in overall retention with increasing vacuum. Though only showing a small dependence, it is important to note for optimization of the papermaking process. This simple relationship is contrary to that found in another study [m] of the affects of applied vacuum on retention in a DDJ. This other study fits a fourth order quadratic to retention versus suction with an initial decrease due to increased flow rate and then a subsequent increase due to clogging of the screen. This does not allow for mat formation and relies on clogging of the screen by filler particles as seen when a DDJ is used for pulp suspensions with high filler content which does not resemble the papermaking process. Clogging is not accounted for in the design of the DDJ and leads to inaccurate, erroneous readings.

Experiments from Chapter 2 show that the forming fabric selection affects the overall retention results. Increasing the filler content in the pulp suspension increases the importance of fabric selection. The forming fabric characteristic that most closely predicts overall retention results is air permeability. The air permeability is a measure of the resistance to flow through the fabric. Instantaneous flow resistance can be correlated to the instantaneous retention of solids passing through (or depositing on) a porous media. The formation of a pulp mat can be thought of as a filtering process with a porous media that continually builds up, decreasing the instantaneous permeability and therefore increasing the instantaneous retention. The permeability results for forming fabric and adhering fibre mat show that the greatest difference in permeability (and thus retention) between fabrics occurs during the initial drainage stages. Therefore, during the initial forming the fabric selection has a large impact on retention results which can affect the final overall retention of a sheet. The permeability for all three fabrics tested collapses to a single value after a substantial fibre mat has been deposited. This suggests that fabric selection is only significant in the initial forming stages. This is consistent with tests relating the relative magnitude of SFR for forming fabrics and fibre mats [12]. The importance of forming fabric selection is further emphasized when the filler distribution at the wire side is considered. The wire side filler content is, to a certain extent, dependent on initial filler retention as concluded in Chapter 3. Since retention is dominated by the forming fabric in the initial stages of dewatering, and wire side filler content depends on initial filler retention, the forming fabric selection is important in determining wire side filler content, as well as overall retention.

4.1.2 Filler Removal and Migration

The filler distribution found in hand sheets formed under gravity drainage with cationic PCC filler shows an increase from top side towards wire side until a plateau is reached. This profile is different from that seen in standard hand sheets [13]. Hand sheets formed using clay filler showed the typical profile of an increase from top side past center and a subsequent decrease toward the wire side. The difference between the distribution curves is caused by the different charges of filler causing repulsion and attraction with anionic wood fibres. The filler distribution was successfully determined both by sheet splitting and ashing as well as sheet splitting and EDX analysis of the layer surfaces. Tests in the modified hand sheet former using a dilute suspension containing PCC filler showed that a great reduction in consistency can also cause a change in the shape of filler profile to match the ‘typical’ profile in hand sheet forming even when cationic filler is used.

Applying a vacuum during the drainage process in a hand sheet with PCC filler reduces the average filler content. The majority of the reduction is from the wire side of the sheet with the remaining filler essentially unchanged. Hand sheets formed with clay filler show only small changes in filler content and distribution when suction is applied during forming. Previous work by Tanaka et al. [13] showed that applying a vacuum during forming did not change the filler distribution in a hand sheet. This work was only performed with anionic filler and matches the results shown here. The differences are attributed to the different charge of fillers and the retention mechanisms that they promote. Anionic filler is retained by filtration in the fibre mat and cationic filler is retained by both filtration and attachment to pulp fibres. Other similar investigations into the filler distribution involved increasing dewatering rates from elements in a gap former [14,15]. These showed that distributions of filler and mat properties could be influenced if changes to the forming process were applied. Based on the similarities between filler distribution in the modified hand sheet former and previous dewatering tests, the filler distribution can be altered during the forming process with preferential removal from the wire side. The greatest changes occur when a cationic filler is used.

Applying a suction pulse to the wet fibre mat after gravity drainage mimics the process of dry vacuum on a paper machine. In all instances, regardless of filler used, the application of a vacuum pulse subsequent to gravity drainage does not affect the filler content or distribution. This is in agreement with earlier work investigating on-line paper forming and dry suction [16]. The previous study concluded that the filler profile was fixed at the dry-line in the forming process. After the dry-line there is not enough filler mobility to allow for movement and changes in distribution. A more severe process on the fibre mat composition is wet pressing. Szikla [17] investigated the changes in filler distribution due to the wet pressing process. The findings concluded that pressing could not change the filler distribution because the filler is fixed in place. Pressing can remove excess water and, entrained in that, small amounts of excess filler but does not affect the bulk of the filler particles. A parallel can be drawn between the wet pressing results and the dry suction results in the modified hand sheet former. After the initial gravity drainage in this study the consistency of the pulp mat (5.5%) is high enough to prevent substantial movement of filler. There is, however, water removal due to air pulled through the mat. This water is visibly clouded by a small quantity of filler but does not contain amounts substantial enough to change the filler content or distribution of the final sheet.

When hand sheets were formed using both clay and cationic PCC filler a contrast between types of filler retention was seen. During hand sheet forming in this study filler was retained by attachment (deposition) to fibres and filtration by the fibre mat. Retention by attachment is due to electrostatic attraction between the filler and fibres. The filler is retained in the pulp mat as fibres are built up. Filtration retention is due to filler particles larger than fibre mat pore sizes being entrapped as the suspension drains through the mat.

Filler retention by attachment to pulp fibres was found to be largely affected by applied vacuum. This is caused by increased drag on particles due to increased flow rate as a result of the suction. A larger number of filler particles are detached from the fibres with increased suction. The largest difference is seen at the wire side. This can be related to the change in SFR caused by increased suction which occurs to the greatest extent at the wire side [15]. SFR can be related to open area in the sheet; a higher SFR corresponds to a lower open area. The smallest open area in a pulp mat occurs towards the wire side which results in a higher local velocity in this area. Since filler particles retained by attachment are affected by local velocity, this increase at the wire side causes a higher local increase in drag. The higher removal of filler from the wire side is a result of the higher local drag on particles. A previous study determined the affect of increased channel flow rate on particle removal [18]. This showed that increased flow rates increase detachment which is similar to the action of filler removal from the wire side of a fibre mat. The results of channel flow can be extrapolated to infer that increasing flow rate by applying suction will increase the amount of filler removed from pulp fibre surfaces thus providing further confirmation of the results.

Filler particles that are not attached to pulp fibres by electrostatic attraction may be retained by filtration. In this study the retention of clay was predominantly by filtration. Filler retained by filtration is only slightly affected by applied suction as seen by the small changes for clay when a vacuum is applied. The reason for the small affect on filtered particles is that the fibre mat compaction further entraps particles that are already larger than the pulp mat pore sizes. Though the increasing flow rate will increase drag on filtered particles, similar to attached filler, the increase does not overcome the physical barrier provided by the pulp mat. Theoretical work by van de Ven [11] showed a drastic increase of filtration retention with increasing particle size (or decreasing mat pore size). This would indicate that the reason provided for vacuum having little effect on clay particles is correct.

Forming hand sheets in two layers shows that filler particles migrate during the forming process. Filler particles from the upper pulp suspension are seen to migrate through the sheet and are retained in the lower layer. Though the migration is increased slightly when vacuum is applied it is not great enough to compensate for poor initial retention. A comparison of hand sheets formed with PCC in the lower suspension and clay in the upper suspension with those of reverse layering showed a difference in the total filler profiles. When clay is used for early stages of forming there is a decrease in filler content at the wire side regardless of the filler type (anionic clay or cationic PCC) used in later forming. The reason for the lower wire side filler content is a poor retention of filler in the lower half of the sheet. The majority of filler from the lower portion of the pulp suspension is lost before a sufficient fibre mat is developed to facilitate retention. Filler from the top portion of the pulp suspension is then filtered as it drains through the fibre mat formed earlier in the drainage process. The filler from the top portion of the sheet is not able to migrate far enough to overcome the poor initial filler retention. This highlights the importance of initial filler retention. If filler retention is not high in the beginning of the forming process it will result in poor surface filler content. It is also evident that filler with different properties such as charge, size and possibly shape will have different distributions as well as fill the sheet, or build up, in different manners.

4.2 Contribution to Knowledge

The knowledge from this work provides further insight into the affects that applied vacuum has on the paper forming process. More specifically the work highlights how vacuum affects retention, filler distribution, and filler migration. This work also provides an apparatus that can be used to further elucidate the affects that various parameters have on the fibre mat and filler particles as described in Section 4.3. The apparatus allows for tests performed under conditions near to those on a paper machine which was not previously possible with hand sheet forming. More specific contributions to knowledge are as follows:

1) Confirmation that, even with mat formation, the dominant variable in determining retention is the presence of chemical retention aids which had previously been stated only in the absence of mat formation.
2) A linear relation was shown between applied suction and overall retention.
3) The importance of forming fabric selection was highlighted through overall retention studies. Fabric selection affects the final overall retention with the highest influence during the initial stages of forming when wire side filler content is most greatly affected.
4) An understanding that different filler types will not only have different retention levels but also different z-direction filler profiles under identical forming conditions. The ‘typical’ distribution is realized if anionic filler is used.
5) A confirmation by tightly controlled laboratory study that applied vacuum during dewatering (thus increased dewatering rate) affects the filler distribution of cationic filler by preferential removal from the wire side. This is in agreement with general mill observations.
6) It was shown that anionic filler (that retained predominantly by filtration) is only slightly affected by applied vacuum. This is in agreement with previous work that concluded that the changes were negligible.
7) The investigation of filler migration showed that different filler types fill a sheet differently and may result in different filler profiles. This also showed that during sheet forming filler particles can migrate from upper layers of the suspension towards the wire side.
8) Retention levels were shown to vary during the forming process. Before mat formation filler retention is low and increases with basis weight. The majority of filler retained in a hand sheet is from the upper portion of the pulp suspension.
9) The importance of initial filler retention was highlighted. It was also shown that poor initial filler retention cannot be accounted for by migration of filler from upper layers of the sheet.

4.3 Recommendations for Future Work

There are still a number of experiments that can be performed using the current apparatus to provide further insight into the effects that suction boxes have on filler particles and the paper sheet during forming. Some of these experiments are extensions of the current work and will provide more elaborate details of the retention effects as outlined above. Others are new experiments designed to provide insight into the possible aspects of retention differences that have been illuminated through this work.

The original design of the turbidity meter as installed on the apparatus cannot provide turbidity measurements throughout the entire forming process because the water below the forming fabric contains high levels of fines and filler. As filler content in the water increases it eventually reaches a point where the laser attenuation is 100% and no reading can be obtained. Modifications to the turbidity meter to limit the width of the channel over which turbidity measurements are taken will allow for study of turbidity over the entire forming process. By calibration of the turbidity meter with samples of a known fines and filler content it would be possible to determine the concentration of each component in the water below the forming fabric. This would allow for the determination of points in the process that most greatly affect fines and filler removal and allow for differentiation between the two substances.

A high-speed camera can be used to capture images of the fibre mat as it is being formed in the apparatus. These video images can be compared with data from the turbidity and permeability studies to attempt to draw comparisons between the measured characteristics and the physical build-up of the fibre mat. This can also provide insight into the physical mechanisms of fibre and filler retention during paper forming and differences in the forming process caused by different forming fabrics.

In this study it was identified that the forming fabric affects the overall retention during forming. The overall retention results were best correlated to the manufacturer's measured air permeability. The air permeability is an indication of the different system flow properties that the different fabrics produce under identical conditions. The correlation was not perfect and it is likely that the shape properties (or weave pattern) of the forming fabric also play a role in the retention. Experiments should be performed to determine what effect the fabric shape properties have on overall retention. One method to obtain these results would be to perform retention tests on fabrics of different weave pattern under identical flow conditions. The flow conditions can be matched between fabrics by varying the applied suction to provide identical drainage velocity and thus correlation between retention and shape factors can be determined.

In paper forming on a gap former the pulp mat is squeezed between two forming fabrics. At various points in the forming process suction is applied to one of the forming fabrics while the other is exposed to the atmosphere, causing a pressure drop across the forming fabrics and fibre mat. Since the fibre mat is adhering to both fabrics during this process but is being pulled away from one and towards the other, there is a possibility of the fibre mat being pulled from the fabric that is exposed to atmospheric pressure. There is currently no understanding of the possible system parameters, such as furnish, consistency, basis weight, vacuum strength and duration, etc., that would cause (or prevent) this from occurring or the effects that it has on the forming process. By forming a sheet in the modified hand sheet forming apparatus, turning it over and placing a second fabric below the fibre mat, this phenomenon, and the parameters that affect it, could be studied by analysis using video data.

It has been identified that the hydrodynamics in the forming process have an affect on the z-direction filler distribution in the finished paper product. Vakil [19] hypothesized that the flow path on an individual fibre during the forming process will follow a path based on the average velocity over a circle with a diameter equal to the fibre length. From this it follows that a filler particle, because of its size, would tend to follow a flow path based on the point-wise velocity field. Given that the velocity is highest in areas of openings in the forming fabric, and lowest in areas of yarn crossings, it stands to reason that the fibre mat that builds up over the forming fabric opening would have more filler particles passing through it and thus a tendency for higher filler concentration. In measuring the z-direction filler distribution using SEM/EDX analysis, Modgi [20] noticed that the filler distribution was non-uniform in the x-,y-directions and attributed this to random fluctuations. A serial grinding of a paper sheet, that is formed on, and left attached to, a forming fabric and a subsequent systematic SEM/EDX analysis on the filler content in the sheet can provide a three dimensional mapping of sheet filler content. This filler distribution can then be related to the weave pattern of the underlying forming fabric to determine if the x-,y-direction variations in filler can be correlated to forming fabric weave pattern.

Another pattern introduced during the paper forming process is wire mark. Wire mark can be seen on the surface of a paper sheet that is in contact with the forming fabric [21]. Though caused in part by the forming fabric surface geometry, the wire mark does not necessarily follow the physical pattern of the forming fabric. Through the use of SEM/EDX analysis it is possible to determine if the filler distribution on the wire side of a sheet is affected by the wire mark or if a relation between the two can be determined.

Further studies of filler distribution and migration should be performed to provide a deeper understanding of how some of the parameters touched on in this study may change the outcome. Given the increased interest in additive layering it would be beneficial to understand the affects of using retention aids in only the lower portion of the hand sheet. Also of interest would be to modify the charge of filler particles (PCC and clay) to determine if the results would be different with reversed or increased charges. This, along with including other filler types, would allow for the determination of the affect of particle shape on distribution and migration. It could also be interesting to determine how mat permeability variations change the filler removal to understand at what point attached filler begins to be removed.

4.4 References

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Appendix A: Apparatus Construction

Purpose of Construction

A modified hand sheet forming apparatus was constructed to allow for an investigation of the effects that various system parameters have on the forming process and the retention of fibres, fines and fillers during hand sheet forming. Standard hand sheet formers do not allow for the collection of data during the forming process and form paper under conditions far removed from those of the actual paper machine. It is too costly to run mill trials to determine the fundamental effects of most system parameters and trial scale machines are often too complex to isolate the effect of changing a single variable. The modified hand sheet former simplifies the forming process sufficiently to allow for data acquisition while maintain the important system parameters such as consistency, forming fabrics and suction near to paper machine levels. This allows for closer comparison of laboratory results with the actual paper forming process and to provide more meaningful data for understanding of the industrial process. The idea for the apparatus construction was first put forth in a CRD proposal by Green [1] in 2008 and further developed upon to its final construction as described herein. The apparatus follows similar design features as that designed by Wegner et al. [2], which is a modification of Britt's DDJ [3] but incorporates measurement of system parameters such as pressure drop and fluid velocity as well as allowing for sheet formation.

The modified hand sheet former can test the affect of a number of system parameters on the forming process and retention of suspension components. As further hypotheses are proposed the tests that can be performed will expand. To this point the possible variables that can be tested are: suction pressure, forming fabric selection, filler type and loading, chemical retention aid type and loading, and suspension consistency and mass. Experiments can be performed to determine the effects that these parameters have on the retention (fibres, fine, fillers), drainage, and permeability of the fibre mat during forming.

Apparatus Features

A schematic of the modified hand sheet former is shown in Figure 6. The apparatus can be broken into three main component parts; the test chamber, the vacuum chamber, and the electronics. A photo of the final apparatus construction can be seen in Figure 22.

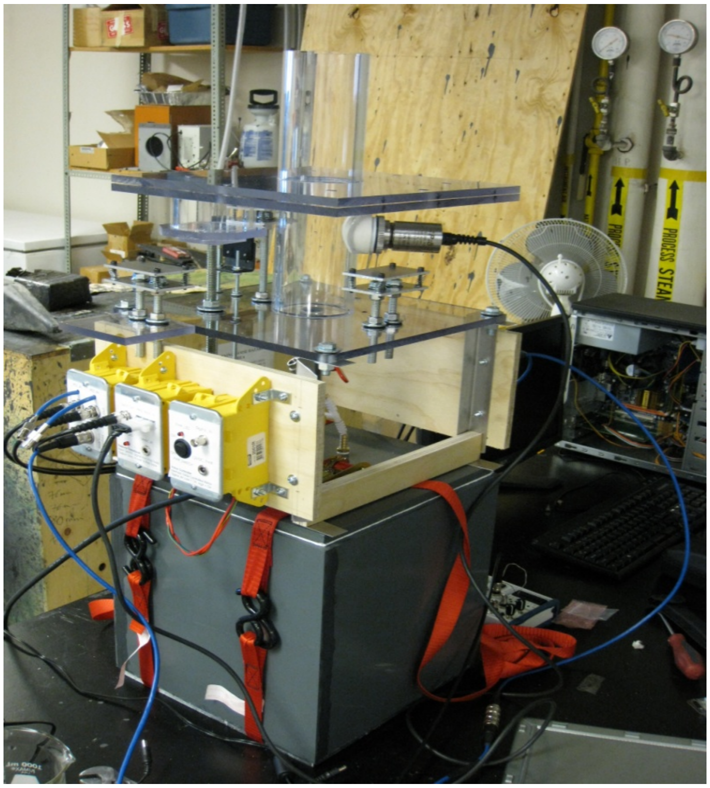

Figure 22: Modified hand sheet forming apparatus

The apparatus test chamber was constructed of a 3” (75mm) diameter, 6” (150mm) high acrylic cylinder below a forming fabric. Another 3” (150mm) diameter acrylic cylinder is mounted above the forming fabric to act as the top portion of the test chamber. The cylinders are connected by square acrylic sheet flanges with gasket sealing around the forming fabric to prevent leakage and air entrainment during testing. Clear acrylic cylinders were chosen so optical access was available to all areas of the test chamber to allow for monitoring during the forming process. This also provides for future tests of hand sheet forming while using a high-speed video camera to capture the forming process.

The lower portion of the test chamber contains a flush mounted pressure transducer (GP:50 Model 218-C-SZ-10-GS) mounted 1” (25mm) below the forming fabric in the chamber wall which provides the pressure difference across the forming fabric and fibre mat during the sheet forming process. A turbidity meter is also installed below the forming fabric. The turbidity meter consists of a 6mW 635nm laser diode on one side of the test chamber opposite of which is mounted a photodiode. As the hand sheet is formed the amount of light reaching the photodiode from the laser will be attenuated in proportion to the turbidity of the water. This is an indicator of the amount of solids being lost through the forming fabric. Calibration of the turbidity with standard solutions can provide a breakdown of components in the suspension below the forming fabric.

An ultrasonic distance sensor (Senix Model TSPC-30S1-232) is mounted above the top portion of the test chamber, which is open to atmosphere. The ultrasonic distance sensor provides accurate measurement of the height of the pulp suspension above the forming fabric during sheet forming. These readings allow for the calculation of the average velocity of the pulp suspension which can be used with the pressure drop across the forming fabric and fibre mat to determine the instantaneous permeability.

Vacuum Chamber

A vacuum chamber is connected to the lower portion of the test chamber by a solenoid valve and ¾" (20mm) PVC piping. The 25L vacuum chamber is constructed of ½" (13mm) thick PVC sheets connected by PVC cement with silicone sealing around a removable lid. The vacuum chamber size was designed so that the suction pressure would vary by less than 1% throughout the experimental process which is defined as the time between the solenoid valve opening and all of the fluid in the test chamber draining into the vacuum chamber. An analog pressure gauge is fitted to the top of the vacuum chamber to determine the chamber set vacuum before commencement of the experiment. The vacuum chamber is connected to a laboratory vacuum pump (Cole-Parmer RK-79200-30) which allows for adjustment of the chamber pressure between 0 and -60kPa. This allows for testing of drainage under vacuum conditions found on a mill scale paper machine.

Electronics

The commencement of the experiment is controlled by a PC with a LabView program through a data acquisition (DAQ) system. The DAQ provides an output signal to a relay which activates the solenoid valve and drains the pulp suspension. The input signals from the pressure transducer, turbidity meter and distance sensor are filtered using a low-pass Butterworth filter with a cut-off frequency of 7.5kHz to filter electronic noise introduced by surrounding electromagnetic radiation [4]. This requires a sampling rate of at least 15 kHz which can be realized using the installed DAQ. The LabView program also provides an output signal through the DAQ for operation of a high-speed camera set-up (for future experiments) and input and storage of signals from the pressure transducer, turbidity meter, and distance sensor for later processing. All of the electronic components employed in the experiment require an excitation power source for operation which is provided by a ±15V power bus in the cases where a power source is not provided by the equipment manufacturer.

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