Fluid Flow Through and Deformation of Wood Fiber Networks

Patrik Pettersson
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Preface

The presented thesis is the result of a collaboration between Luleå University of Technology, Sweden and Metso Paper, located in Sundsvall, Sweden, during the years 2003-2009. The work was financed by The Swedish Research Council and Metso Paper. I would like to mention some of the persons, whose contributions have played important roles, in order to make this work possible.

First of all I would like to thank Professor Staffan Lundström and Dr. Tomas Wikström for giving me the opportunity to do this interesting research work within the area of flow through wood fiber network. Especially I want to express my thanks to them for the endless support and trusts for my research and for supervising my work during these years.

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Patrik Pettersson

Sundsvall May 2009
Abstract

Cellulose-based commercial items such as paper and laminated flooring are vital to the local economy of northern Sweden. These products are commonly manufactured in suspension where fluids such as water or air are drained through the fiber network in some value-added steps in the manufacturing process. It is crucial to gain in-depth knowledge of the fluid-solid interaction between the carrier fluid and the cellulose product as this may lead to advances in products and processes.

The focus of this thesis was to study the flow of a Newtonian fluid through a compressible cellulose fiber network; both air and water were considered. The work was divided into a number of studies in which information was gathered regarding the ease at which water flows through the network under essentially steady-state conditions to define the permeability of the fiber network. The difficulty is that the network may deform under the loading of the flowing water. In these initial studies a number of novel experimental devices were devised in which the in-plane permeability, i.e. normal to the direction of the principle axes of the cellulose fibers, and uniaxial compressive yield stress were determined as a function of solid fraction. The exact mechanism by which the network deforms under load remains an open question. To start with, a flow field study was performed in a unit operation, i.e. “Metso Continuous Press”, compared with collected field data in a mathematical model developed in this thesis.

A mathematical model was established to study the mechanics in how the network deforms under load in a one-dimensional filter press. Results from the first part regarding the permeability and the compressive yield strength for the papermaking fibers were used. Simulated prediction was compared with the experimental results. A rate dependent lag was found for the fiber network.

The study was continued to examine pressure filtration in which the cellulose network deforms dynamically under the action of an externally applied load. An open question in this case is the behavior of the water internal to the fiber network. During compression, initially there is a reduction in pore volume and an increase in the number of fibers in contact. At some degree of compression, the number of fibers in contact is such that further compression can only occur by the individual fibers themselves through deformation of the fiber. This process was modeled, and it was considered that the energy required to compress the network must balance the viscous dissipation rate. Closure equations were developed and tested experimentally by comparison to the pressure developed to drive the piston. Good agreement was found. In subsequent work an attempt to confirm the form of this relationship independently through novel visualization methods was performed, i.e. positron emission tomography. The utility of this approach may be discussed.
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Part I

SUMMARY
1. Introduction

In this work the area of flow inside wood fibrous materials was explored. Wood fibrous materials are found in the pulp and fiberboard industries. Processes such as the pre-press and the hot press in the fiberboard industries, washing and displacement equipments such as presses, atmospheric and pressure diffusers, screens, formation equipments etc. in the pulp industries, are examples of unit operations where flow of fibers is of interest. All these unit operations benefit from increased knowledge the interaction between the flow field and the wood fiber suspension.

1.1 Process description MDF industry

A short description of a typical Medium Density Fiberboard (MDF) process is given below.

![MDF Process Diagram](image)

**Figure 1-1.** Typical MDF process

Wood is debarked and chipped in a wood yard. A screen removes chips of undesirable sizes, the remaining wood chips are cleaned in a chip washer in order to remove sand, metal and other foreign particles, see Figure 1-1 that shows the flow of material, from log to MDF panel.
The wood chips are then pre-steamed to a temperature of 50-80°C in a surge bin after which they are fed into a pre-heater by a compressing screw (plug screw). The plug screw compresses the chips to a solid plug that makes it possible to retain a high pressure in the pre-heater; it also lowers the moisture content of the wood chips by dewatering them through the screw housing. In the pre-heater, the wood chips are heated to ~170°C, which is accomplished by condensing steam at a pressure of ~ 9 bars on the surface of the wood chips. The purpose of heating the chips is to soften the lignin before grinding them into fibers. This is mechanically done in the Defibrator. Within this unit there is intense steam generation (evaporation of water due to frictional work) and the chips disintegrate into fiber-bundles and individual fibers. The typical power consumption of a Defibrator is 150-250 kWh/t of dry fibers. The steam is subsequently used to transport the fibers to a dryer via a blow valve and a blow line. Adhesive can be added in the blow line or in designated glue blending equipment after the dryer.

Hot air is then used to dry the fibers in either a single-stage or a two-stage dryer. The fibers enter the dryer at a very high velocity. During transport through the dryer, water is evaporated from the fibers; the fibers and humid air are then separated in a cyclone. From the dryer outlet, the fibers are transported to a mat former, often through a sifting device in order to remove glue lumps and other undesirable objects that might damage the hot press. The mat former, which can be pneumatic or mechanical, produces a fiber mat of density ~30-50 kg/m³.

A pre-compressor compresses the fiber mat to a density suitable for the hot press. The fiberboard is pressed and cured in the hot press, which is usually a continuous press; for door skins or other types of panels with surface structures, single or multi-opening batch-presses are commonly used. The panels are then cut to storage size and then cooled in a cooling wheel before storage. After sanding, the panels are cut to obtain their final dimensions.

The process pre-press and hot press incorporates the flow in wood fiber network. More knowledge of fiber-gas flows would therefore speed up the development of these processes. Controlling the flow of gas that is squeezed out from the preformed fiber mat in the entrance of the hot press is of particular interest where the relative fiber-gas flow plays an important role and is therefore also dealt with in this thesis.
1.2 Process description chemical pulping industry

A short description of a typical chemical pulping process is given below. Figure 1-2 shows the flow of material from log to bale pulp.

![Diagram of a chemical pulp mill process](image)

**Figure 1-2.** An example of a fiber line in a chemical pulp mill by Metso Paper.

Wood is debarked and chipped in a wood yard. A screen removes the chips of undesirable sizes and the remaining wood chips are cleaned in a chip washer in order to remove sand, metal and other foreign particles.

In kraft cooking, fibers are liberated in a chemical process where predominately lignin is dissolved; dissolved lignin is separated from the fibers in subsequent washing steps. Dissolved organic material and spent cooking chemicals, referred to as black liquor, are brought to the pulp mill’s recovery system, where the organic material is burnt to generate energy and the spent cooking chemicals are regenerated to be reused as fresh cooking chemicals. Modern pulp mills are thus net producers of energy.

The screening process is a gentle treatment, due to the low concentration of fibers. Fiber properties are not, or just slightly, affected. The main purpose of screening is basically to remove impurities in order to produce a pulp composed of individual fibers. In a mechanical pulp mill,
the screening process can also serve the purpose of fractionating the pulp, i.e. to divide the pulp into an accept fraction and a reject fraction. The reject fraction, which contains coarser and longer fibers, is treated in reject refining and then re-mixed with the accept fraction to give a smaller amount of pulp of special quality enabling the making of multi layer paper.

Washing is an operation that takes place in all kinds of pulp production. The purpose of washing is basically to wash out dissolved organic and inorganic material and thus to obtain a clean pulp. Depending on the requirements, a number of washing stages in series use wash water in a counter-current mode. A cleaner liquid that is fully miscible with the liquid inside the pulp suspension is used to displace the liquid inside the pulp suspension. The fluid is pressed through the fiber network and through the perforated dewatering surface whilst the fibers remain.

The main function of dewatering of fiber suspension by pressing is to achieve a high pulp consistency out from the unit operation for the forthcoming process steps. Due to the high consistency, a high washing efficiency is realized simply by pressing out the surrounding liquid. The high consistency has economical aspects for the pulp mill. Most of the spent chemicals will be reused and the washing system can be considered as closed. The press is based upon two rotating perforated cylinders, where the pulp suspension is forced into the contraction between the rotating press rolls. In order to attain the high consistency in the compressing zone a quite high pressure must be applied. The applied pressure is used in order to squeeze out the fluid through the wood fiber network as well as from the fiber itself, and through the perforated rolls whilst the fibers remain. The total network volume is thereby decreased and the consistency increased.

Displacement and dewatering techniques can be combined in a wash press unit. The vat immediately before the press nip can be used for the displacement washing where the unclean liquid is removed and replaced by a cleaner one. The dewatering technique is generally based upon compression and the dewatering may take place on at least two scales: A macro flow between the fibers and out from the suspension and a micro flow out of the fibers when they are squeezed towards each other. The importance of these two flows will be dealt with in this thesis.

The bleaching process has the target to increase the brightness by removal of remaining lignin and discoloration of chromophoric groups in the pulp. This process exposes the fiber surface for chemical reaction. Removal of the remaining lignin makes the fiber wall thinner, i.e. the fiber rod becomes slimmer. The discoloration chemicals affect the surface chemistry and physics of the fiber.

A relative flow between fibers and liquid occurs in processes as cooking equipment, screens, washing and dewatering equipment etc. More knowledge of the fiber-liquid behavior would increase the potential to improve these processes.
1.3 Flow phenomenon during dewatering/deaeration of fiber suspension

Close to the final stage of the manufacturing of fiberboards a fairly thick network of loosely entangled fibers is compressed to often less than a tenth of its original thickness in a converging belt press. Consequently a large amount of air must be evacuated out of the network. During this process the fibers becomes subjected to a force generated by the flow at the same time as they are compressed between the belts. The force from the air flow is thus balanced by the entanglement of the fibers and finally the friction towards the belts. It is likely that the larger the compression is the larger is the stiffness of the fiber network. At the same time it is also likely that the forces from the flow are highest in low permeability areas, that is, for dense fiber networks. Anyway experiments as well as observations in production reveal that if the velocity of the belts becomes too high the fiber bed will burst. In these cases the strength of the fiber network is too low as compared to the forces from the air that is pressed out from the fiber network.

During pressure filtration of wood fiber suspensions, water is squeezed out from the network when the fibers are moving towards each other. The applied force on the wood fiber suspension can be split into at least two parts. These parts can be simplified by the use of a spring and damper system. The spring represents the stiffness of the wood fiber network and the damper describes how easily the fluid flows through the fiber suspension. The stress level is at a constant value in each layer inside the compressed volume, i.e. equal to the applied pressure. However, the different phases will contribute differently to the applied load. A longer distance to flow generally gives a higher resistance to flow. Hence, the sum of the load of the different phases is described by Terazhagi’s principle which states that in each point the sum of liquid and solid load is equal to the applied load on the suspension. By applying this principle the physics of consolidating a wood fiber network may be analyzed. Closest to a perforated plate, through which the fluid is flowing, the solid phase can be considered to carry almost the entirely applied load as long as the pressure drop of fluid over the perforated plate is considered to be much lower compared to the applied pressure. The liquid pressure closest to the perforated plate can in its turn, due to the high solid pressure, be considered to have the same pressure as the one that is acting on the outlet side of the perforated plate. How much of the total load that is carried by respectively phase is totally dependent on the filtration speed, the amount of suspension that is compressed and the characteristics of the wood fibers. Imagine a closed volume with a movable piston moving towards a perforated plate which will be the separation surface between the fluid and fibers. A number of different pressure scenarios are possible inside the wood fiber network when compressing at low, medium and high speed, which is explained in the paragraphs below. Valid for all cases is that the fibers are moving towards each other and fluid is forced to leave the cavity driven by a pressure gradient.

At low filtration speed the fluid flow generates a low drag on the fibers in the network, the generated fluid pressure will due to that be much lower compared to the compressive yield
strength of the fiber network, this is true for each point inside the compressed volume. Hence, since the fluid pressure in every position is much lower than the compressive yield strength of the wood fiber network, the solidity profile of fibers will be close to constant in the direction of filtration. The estimation of the pressure drop of the fluid through the network can be determined by use of Darcy’s law. Increasing the filtration speed will result in an increased drag from the fluid, when flowing through the fiber network. Eventually the drag will become higher than the compressive yield strength of the wood fiber network, a consequence from this is that fibers will move towards the filtration plate and generate a non-linear pressure profile in the pressure filtration direction. When the filtration speed is increased even further, the system reaches an even higher solidity at the filtration plate due to the increased drag. Eventually the hydraulic pressure drop will peak and the yield stress in in-plane direction is overcome, hence channels are introduced into the system. The generation of channels drastically decreases the hydraulic pressure drop in the system, i.e. this decreases the applied load onto the process.

The solidity profile is related to the networks’ permeability and compressibility which are related to the morphology of the wood fibers. Having this in mind it is interesting to notice that dewatering of a relatively compliant and low permeable hardwood pulp can in reality be done much faster than for a relatively stiff and high permeable softwood pulp. Hence, the short and thin fiber has a lower solid network strength compared to the long fiber, (Benningon, Kerekes et al. 1990), the generation of channels are due to that reached at an earlier hydraulic pressure gradient. Unfortunately, the channeling effect will decrease the washing efficiency since the fluid is not flowing through the entire suspension.

1.4 Thesis objectives and outline

In the present thesis, the objective was to clarify and describe the procedure that has been performed in order to predict the pressure generated when dewatering/deaeration wood fiber suspension with fairly high basis weight as is common in pulp and fiberboard mills. Some material models had to be known in order to fulfill this objective. This includes a material model describing how easily the fluid can flow through the wood fiber network, and a material model describing the ability the fiber suspension has to resist compression, compressibility of the fiber suspension. How these models come into play during compression of wood fiber suspension is addressed in this thesis.

This thesis is divided into two parts. The first part consists of seven chapters, summarizing the results of the work described in the appended papers, named Paper A-E. Apart from being a summary, the first part put the present work into its perspective. Next chapter starts with a summary describing the theoretical approach by a number of researchers in the area of flow in wood fiber suspensions. The chapter is an overview of various experimental approaches and the results when determining material models for wood fiber network. It is followed by an introduction of wood fiber network as a porous material.
Chapter four introduce the strong need for accurate permeability data and the importance it plays with the mechanics of the solid network stress for dry fiber networks acting in a MDF-press and for pressure filtration of paper making fibers. The chapters can be seen as an overview of the context in the appended papers, Paper A, C and D. Followed with a chapter that introduces a theoretical analysis of a flow field study inside a wood fiber suspension and a pressure filtration study of a pulp suspension. Simulations and results from experiments were useful tools in order to make the correct assumption on what is actually the dominating part in these particular studies, these can be seen as an overview of Paper B, D and E. The second part of the thesis consists of five appended papers, Papers A-E, representing the core of the thesis. Papers A - E are written in order to fulfill the objective of the work.


Authors contributed to the work

Paper A: Developing of experimental equipment, design of experiment, evaluation of data and writing was performed by Pettersson P (PP) under guidance of and supported by Wikström T, (TW) and Lundström TS (SL).

Paper B: Modeling work and evaluation were done by PP. Discussion with and guidance from SL, and TW. SL & EW contributed with work in the area of modeling.

Paper C: Developing of experimental equipment, design of experiments, evaluation of data and writing were performed by PP under guidance of SL, and TW.

Paper D: Design of the experiments was done by PP. Modeling and simulation work was performed by PP and Lindgren K under guidance of SL and TW.

Paper E: Design of the experiments was done by PP and (TW), developing of material model was performed by PP. Modeling work, simulations and validation experiments were performed by PP and Martinez M (MM).
2. Flow in porous material

2.1 Permeability

This study covers a part of the manufacturing process of Medium Density Fiberboards, (MDF) and pulp suspensions. In a more general form the material can be described as a suspension of loosely entangled fibers. The suspension is compressed in a press to often less than a tenth of its original unstressed thickness. During this process, a large amount of fluid is forced through the porous mat generating pressure on it due to a flow resistance between the fluid and the fibers. In the most general form (Wahlström 1960) and (Asklöf, Larsson et al. 1964) studied the removal of water by conducting a press study with felts, and many of their conclusions are still valid. The main objective of their study was to investigate the factors governing water removal and the moisture distribution of a suction press. During the dewatering process, the fiber network is exposed to a drag force generated by the flow of the fluid. The magnitude of this force is dependent on the type of fluid and how easily the fluid can flow through the network, which is commonly described by the materials’ permeability. A gas flow at a specific flow rate generates a much lower drag force on the network compared to what a liquid flow at the same flow rate would produce due to the differences in viscosity between the gas and liquid. The solid load response, in its turn, is often expressed in terms of the compressibility of the fiber network. The governing material parameters when considering compression of fiber suspension are the permeability and compressibility of the suspension (Ingmansson, Andrews et al. 1959) and (Vomhoff 1998). If the force on the network generated by the flow becomes too high, the fiber network will collapse. In order to mimic the flow and the corresponding pressure gradient, the resistance to flow must be found. On behalf of the fluid flow, one reliable method to determine the resistance to flow in complex network is to measure the resistance to flow at discrete points and to fit suitable resistance models to the results. Measurements of the resistance to flow of porous materials are, however, not straightforward. To start with, flow through porous material does not generally follow Darcy’s law (Dullien 1992). There are at least three possible reasons for this. i) The Reynolds number, in many cases, becomes too high and inertia effects must be considered. The inertia effect is usually dealt with by using the Forchheimers Equation (Whitaker 1996) which may be written:

\[ -\frac{\partial p}{\partial x} = \frac{\mu}{k} v + \beta \rho v^2, \]  

(2-1)

where \( p \) is the pressure, \( v \) the superficial velocity, \( \mu \) the viscosity, \( k \) is describing how easily the fluid flows through the fiber network and \( \beta \) parameters of the porous media, and \( \rho \) the fluid density. If \( \beta \) is set equal at zero, \( k \) becomes equal to the permeability and the Darcy’s equation is found. Hence, in order to use Eq. (2.1), two material parameters must be determined. ii) Besides inertia effects, if the pressure drop caused by the flow rate overcomes the yield stress of the fiber suspension, the network may deform. This phenomenon has been shown to result in a linear
pressure velocity relationship up to a certain pressure difference, while above this pressure a
deviation from the linearity occurs, (Belkacemi and Broadbent 1999), (Zhu, Pelton et al. 1995).

iii) The non-Darcian behavior can also be attributed to the molecular effect being important for
gas flow at low pressures in very small pores. The effect is that measured gas permeability is
higher than for a corresponding liquid permeability in the same porous media (Bear 1972). This
is explained by that the mean free path of the gas molecules approaches the dimensions of the
pores. This results in a Knudsen flow, implying that there is a slip between the walls of the pores
and the gas. This would result in a too high measured flow rate for a given pressure drop. For N₂
at a pressure of one atmosphere and a temperature of 300 K, the mean free path is 22 nm
(Thompson (1972)).

Several methods for the experimental assessment of the permeability tensor have been proposed
since the first experiments by Darcy, ((Sullivan and Hertel 1940); (Ingmansson, Andrews et al. 1959); (Lindsay 1990); (Gebart and Lindström 1996); (Weitzenböck, A.Shenoi et al. 1997);
(Lundström, Stenberg et al. 2000) and (Lundström, Toll et al. 2002)). Most of the methods are
based on one of the two fundamentally different principles, Figure 2-1: i) parallel flow, by which
the liquid is made to flow in a controlled direction through the porous sample, i.e. the Darcy
experiment. ii) radial flow, by which the liquid is injected at a ‘point’ and flows freely in all
directions (usually in a plane).

![Figure 2-1](image.png)

**Figure 2-1.** The multi-cavity parallel flow cell in the LHS, the RHS shows the radial flow cell.

Either of these principles may be applied in a variety of ways, e.g. by pumping the liquid at a
constant flow rate or at a constant pressure drop. Parallel flow measurements can be carried out
under steady state conditions (Lundström, Stenberg et al. 2000). One drawback of this method is
that porosity, and consequently permeability, differs near the walls of the cell as compared to the
porosity in the rest of the bulk. Another drawback is that errors in permeability values are
obtained if the flow is not in the main permeability directions. Only a few studies are available regarding gas flow. (Sullivan and Hertel 1940) estimate the permeability of glass fibers, while (Bouazza and Vangpaisal 2003) focus on clays. In both cases, the measurement is carried out in a fixed control volume where the pressure drop is carefully measured at a constant flow rate in a geometry similar to the parallel geometry.

Yet another approach to determining permeability that is often applied to fibrous material is to use a dynamic compression equipment (Buntain and Bickerton 2003). The fibrous network response is known in these kinds of experiments and permeability can be determined from the hydro-dynamical pressure drop according to the Terazhagi’s principle, (Vomhoff 1998); (Ingmansson, Andrews et al. 1959). However, one uncertainty in this kind of experiment is that the volume fraction in the suspension is not generally constant in the dewatering direction (Zhu, Pelton et al. 1995; Lu, Huang et al. 1998), especially when considering the basis weights found in pulp mills.

Several permeability models can be found in the literature, among others is the experimental work conducted by (Lindsay 1990) and (Vomhoff 1998). Neither of them tested permeability at basis weights of 1 kg/m² or higher, even though (Lindsay 1990) measured permeability at a basis weight that was almost 10 times higher than (Vomhoff 1998). The Kozeny-Carman equation Eq. (2.2) gives poor agreement with the permeability of pulp suspensions especially at high porosity values;

\[
 k = (b \cdot S_0^2)^{-1} \cdot \frac{\varepsilon^3}{(1 - \varepsilon)^2}
\]

Figure 2-2. Schematic sketch of the flow domain. For the experiments, the lower platen was formed as a basin, to contain all fluid nearly within the mold.

where \( b \) is representing the Kozeny constant equals to 5.55 for cellulose fibers, \( S_0 \) is the specific surface and \( \varepsilon \) is the total porosity of the pulp suspension. (Ingmansson, Andrews et al. 1959) have shown that the Kozeny constant varies with the porosity of cellulose material and modified the relationship Eq. (2.2) accordingly to the following expression:
\[
\frac{1}{k} = \left[ C_1 \cdot S^3 \cdot (1 - \varepsilon)^{3/2} \cdot (1 - \varepsilon)^3 \right]
\]  

(2-3)

In this equation the empirical parameters \( C_1 \) and \( C_2 \), have the values 3.5 and 57, respectively. However, the porosity in their study was based on the free liquid porosity outside the fibers. This kind of approach is only valid in the low consistency area in an actual press sequence. In the high consistency region, the fibers deform themselves and the porosity within the fibers decreases as well. (Vomhoff 1998) and (Lindsay 1990) have considered the total porosity of the fiber suspension and their models are therefore valid throughout the total pressing sequence.

Results found in literature give a quite wide spread in permeability of wood fiber suspensions. In the area of papermaking industries especially in the paper machine the basis weight is low compared to the basis weight in the area of pulp mills and in the fiberboard industry. Permeability is as mentioned earlier to describe how easily the fluid can flow through a porous material. By letting \( \beta \) in Eq. (2-1) be zero, Darcy’s law is found. Measuring the pressure drop over a single fiber would not represent an adequate experiment when determining the pulp suspension’s permeability, even though the Darcy’s law states that a linear relationship occurs between pressure drop and fluid velocity. Hence, a critical amount of fibers must be expected when determining the permeability of a porous network. However, by studying permeability results found in literature on pulp suspensions with low basis weight the results are dependent on the basis weight. Hence, if the length scale is decreased to only a couple of diameters of the fibers itself one can expect that a non-isotropic material is found. Analyzing the permeability in a similar material, must give a result that is dependent on the length scale, i.e. the materials basis weight. However, by increasing the basis weight eventually the critical length scale is reached and the permeability is moved towards an asymptotic value as long as the permeability is measured in a Darcian flow rate, hence, the former results should not be mixed by the fiber suspensions’ macro permeability.
2.2 Compressibility

The deformation of bodies under stress is described as the materials’ rheology. It describes the irreversible deformation in viscous Newtonian flows as well as the deformation that does not lead to permanent dislocation of elements of the material. Fluid mechanics and the theory of elastic materials concern idealized bodies that obey one exact physical law each, i.e. Newton’s law and Hooke's law respectively. Rheology, on the other hand, concerns real materials that exhibit elasticity and viscosity. In other words, rheology describes materials ranging from solids to fluids. When an elastic solid body is deformed, intermolecular bonds are stretched. An equilibrium is quickly established so that internal stresses are balanced by the external stresses. The simplest case is when the stress is proportional to the deformation (Hooke's law), but materials with a non-linear dependence also exist. The simplest effect is the yield stress, which is the lowest applied stress, which results in a flow of the material. If a lower stress than the yield stress is applied, the body acts like an elastic solid.

To forecast the dominating effects when compressing a fiber suspension, the interplay between fluid and fibers must be known. When contact between fibers increases during compression, an additional pressure appears, on the solid structure, that is caused by the fibers being bent and compressed (Toll 1998). This pressure, termed $P_s$, is related to the compressibility of the fiber network and has been derived for a couple of idealized arrangements in (Toll 1998) to yield the following equation

$$p_s = cE(\varphi^n - \varphi_0^n), \quad (2-4)$$

where $c$ and $n$ are constants dependent on the geometry of the network, the variable $E$ is the modulus of the fibers, $\varphi$ is the solid volume fraction and the subscript 0 denotes initial conditions. The total force generated during pressing is thus shared by the fluid and solid fibers (Szikla and Paulapuro 1989; El-Hosseiny 1991; Vomhoff 1998; Lobosco and Kaul 2001). By using the previously mentioned Terzaghi’s principles, ((Terzaghi and Peck 1948), which state that the total pressure acting on a suspension must be split between fluid and solid pressure, (Grén and Hedström 1967; Martinez 1998). This relationship is described in the following manner:

$$p_t = p_s + p_f \quad (2-5)$$

The consequence of this equation is that hydraulic and solid pressures can be estimated individually. The validity of this assumption will be discussed more in detail especially in the chapter concerning the washing model where it becomes difficult to determine the correct material model especially for pulp suspension using Eq. (2-5).

When analyzing measurements of the solid network stress of a pulp suspension, (Zhu, Pelton et al. 1995) have pointed out that porosity decreases slowly with increasing mechanical stress until yield stress of the fiber suspension is exceeded. This can be explained as a macro movement...
when the fiber network is compacted. (Zhu, Pelton et al. 1995), penetrated fluid through the network and noticed that at small changes in mechanical stress gave a drastically increase in solidity, Figure 2-3, i.e. a consistency profile is generated. A parameter study performed by (Lobosco, Norman et al. 2005) shows that $P_s$ increases at the same rate as deformation of it, this was found to be related to the intra-fiber flow that occurs when fluid is squeezed out of the lumen volume as fibers collapse. Consequently, a higher compression rate thus results in a higher fluid flow resistance out from the fibers and, therefore, an overall higher resistance is necessary to deform the fiber network.

Figure 2-3. Simulated porosity profile found by Zhu et.al, along the z-direction "flow direction".
3. Materials and Methods

3.1 Wood Fiber suspensions

In the pulp industry wood fibers are manufactured by chemically dissolving those components that keep wood cells together to form the original wood structure, mainly lignin. When manufacturing fiberboards the fibers themselves are obtained by separating wood chips in a refiner. The aim of the processes is to manufacture fibers with least possible damage. The quality of fibers is strongly dependent on the morphology of the wood material used. In softwoods, long and slim fibers are dominant while hardwoods have short and slim fibers. The fiber characteristic is also dependent on the location of the tree. Boreal trees grow seasonally, intensively during summer, slower towards autumn and not at all during winter. Early wood fibers are wider in diameter and thin walled, while late wood fibers are narrower but with relatively thicker cell walls, Figure 3-1.

![Figure 3-1. Cross section of different kinds of wood fibers. The early wood fibers have a thinner fiber wall thickness, bigger lumen and bigger cell width than latewood.](image)

The fiber dimensions are strongly dependent on the location inside the tree trunk too. Fiber length increases from the root up towards the middle of the trunk while it decreases towards the tree top. In the radial direction the fiber length and fiber wall thickness is decreased. The overall fiber dimensions in a tree are dependent of wood species and growth rate.

3.2 Solidity

The structural properties in the fiber suspension are dependent on the distribution in fiber length, fiber diameter and fiber wall thickness. Some of these parameters are used when determining the solidity of a network. A number of parameters describing the consistency have been presented for pulp suspension; one important parameter is the solidity described by (Wikström and Rasmuson 1998) and (Vomhoff and Norman 2001). The solidity defines as the total volume of fibers, i.e. total fiber volume in relation to the total volume, illustrated by (Wikström and Rasmuson 1998):

$$\phi = \frac{V_{fw}}{V_{fw} + V_{lw} + V_{l} + V_{g}}$$

(3-1)
where \( \phi \) describes the total solidity for the fiber mat, the fiber wall volume, \( V_{fw} \) and \( V_l \) and \( V_g \) represents the free volume of liquid and gas between the fibers respectively. The lumen volume inside the fibers is represented by \( V_{lu} \), Figure 3-2.

The total solidity for the fiber suspension can also be expressed in terms of the density method suggested by (Vomhoff and Norman 2001):

\[
\phi = \frac{w}{h \rho_{fw}}, \tag{3-2}
\]

where \( w \) is the basis weight [kg/m²], \( h \) [m], the thickness of the sample, and \( \rho_{fw} \) [kg/m³], the fiber wall density. The basis weight is defined as the dry weight of the wood fiber suspension per square meter.

Another approach to describe the concentration inside the fiber suspension is to neglect the lumen volume and focus on the volume outside the fibers. This concentration is described as the fiber suspension’s effective solidity. The effective solidity for the wood fiber suspension is found by using the formulation described by (Wikström and Rasmuson 1998).

\[
\phi_e = \frac{\pi d^2}{4Co} \rho_l \left[ \frac{C_m}{1 + C_m (\rho_l / \rho_{fw})} \right] \tag{3-3}
\]

where \( d \) is the average fiber diameter of the fibers, \( Co \) is the coarseness value mg/m, and \( C_m \) is the consistency by mass or the dryness value being defined as:

\[
C_m = \frac{m_f}{m_f + m_l} \tag{3-4}
\]
4. Fundamental Experiments

In this chapter the design, validation and usage of fundamental experiments to derive material properties are described. The main purpose with these experiments is to give material data as a function of porosity for the cases in chapter 5. It, however, turns that a number of general results are generated direct from these measurements.

4.1 Permeability Experiments

In this thesis two types of parallel flow cells have been used to measure the permeability of wood fiber suspensions. One equipment is used to measure the air permeability in wood fiber networks, and the other equipment is used to measure the wet permeability in pulp suspensions.

4.1.1 Gas permeability unit

The, to my knowledge unique, gas permeability unit is designed for measurements of in-plane permeability as well as out-of-plane permeability, Figure 4-1, Paper A. If the latter direction coincides with one principal direction, the full 3D-permeability tensor can be derived. To determine the permeability for the porous material, Darcy’s law is used.

\[ \frac{\partial P}{\partial x} = -\frac{\mu}{\kappa} V. \]  

(4-1)

![Figure 4-1.](image)

Figure 4-1. Schematic sketch of the measuring cell set-up. Index 1 and 2 denote the inlet and outlet respectively. The pressure transducers, located as illustrated in the sketch measure the pressure drop of the gas.
through the material. During the measurement, air is transported in a tube out from the equipment where the flow rate and air pressure are measured in order to determine the mass flow of the gas. For the in-plane set-up, a pair of rubber cloth was placed at the top and bottom of the porous material. In that set-up the solid plates were exchanged to perforated plates with holes of a diameter of 1mm.

Since air is a compressible fluid, it is necessary to rewrite Darcy’s law Eq. (4-1) in a form dependent on the mass flow rather than the volume flow by usage of Eq. (4-2)

\[ p \cdot v \cdot A_e = \dot{m} \cdot R \cdot T, \]  

(4-2)

where \( R \) is the gas constant, \( T \) is the temperature of the gas, \( p \) is the fluid pressure, \( A_e \) is the cross-sectional area of the cavity, and \( \dot{m} \) the mass flow. By integrating the combination of Darcy’s law Eq. (4-1) and the equation of state for air Eq. (4-2) in the flow direction and by assuming a homogenous porosity profile, the gas permeability is expressed as:

\[ k = \frac{2\mu R T h}{A_e(p_1^2 - p_2^2)} \]  

(4-3)

To derive the out-of-plane permeability, air is forced to flow through a perforated plate placed at the base of the measuring cell and into the network by an applied pressure gradient, cf. Figure 4-1. The air is then allowed to leave the cell through a perforated top wall. The maximum volume of the cavity is 0.19 m x 0.311 m x 0.4 m where the last dimension denotes the height. In the current set-up, flow meters (4 to 25 m³/h, or 30 to 390 m³/h) were connected externally with the permeability equipment at the outlet by a tube with an accuracy of ±0.5% of the calibrated span. In addition, a pressure transducer ranging from 0 to 16 kPa was placed close to the flow gauges in order to determine the mass flow. Pressure transducers (0 to 20 kPa, or 0 to 200 kPa) were also connected to the permeability equipment at the inlet position, marked as \( p_1 \), the sensitive one was used at low pressure levels in order to reduce experimental error. The pressure transducer placed at the outlet had a range of 0 to 7.5 kPa, marked as \( p_2 \) in Figure 4-1. The measurement error of the pressure transducers was ±0.2% of the calibrated span. The height was measured by a linear magnetic position sensor with a measuring length of 1.0 m with a deviation of ± 0.05% of the calibrated span.

The permeability measurements were conducted under stationary conditions in the sense that a constant flow rate was applied through the fiber mat while the height of the cavity was held constant. Since the permeability of the fiber mat is strongly dependent on the solidity, additional measurements were performed by lowering the upper plate. This procedure was repeated until the lowest possible volume of the cavity was reached, with respect to the limit of the pressure transducer or that the maximum load from the compression was achieved.

For the measurement of the in-plane permeability, the solid walls were replaced with perforated plates, and rubber cloths were placed on the top and bottom surfaces to prevent air from leaving the cavity in out-of-plane direction. Air was forced through the sample from the left chamber to
the corresponding right, illustrated in Figure 4-1 where also the positions of the pressure transducers can be spotted.

The systems presented have a few sources of errors such as:

- Pressure losses through the sealing between the piston and solid walls.
- Edge effects in the fiber mat closest to the solid wall.
- Pressure, flow rate and position transducers.
- Non-uniform flow rate due to compression of air.
- Temperature variations inside the cavity due to variation in temperature of the flowing gas.

Some of the sources are more difficult to estimate than others. However, by studying their effects on the permeability in Eq. (4-3), it is possible to distinguish the most sensitive ones. By scrutinizing the parameters, it is obvious that the inlet and outlet pressure must be measured very accurately. In addition to this a pressure loss test without fibers in the cavity was performed in order to study how the flow resistance through the perforated walls influenced the permeability. It was shown that the pressure drop through the walls can be negligible when determining the permeability of a wood fiber network.

A final remark on the performance of the measurement is that a fiber bed with no constraints would compress homogeneously. A hypothesis is that with constraints, for instance due to friction at the side walls, an inhomogeneous material may be obtained, the estimation of the permeability will due to that effect be misleading. Hence, during the permeability measurements the applied force on the fiber bed was logged, showing that the reaction force from the bed towards the piston was decreased during the measurement, i.e. the fibers were redistributed. Hence, the permeability measurement was not established until force equilibrium was reached.

### 4.1.2 Wet permeability unit

To experimentally derive the permeability of the pulp suspension, a permeability unit was developed and designed for measurements of out-of-plane permeability, Paper C. The cavity had an inner diameter and a maximum stroke length of 0.1 and 0.3 m, respectively. The device was designed to let a pressure-driven flow of water pass through the specimen, in the vertical direction from bottom to top, Figure 4-2.

The permeability measurements should be conducted at stationary conditions, i.e. a constant flow rate should be applied throughout the porous material while the height of the cavity is held constant. The results from Darcy's law, Eq. (4-1) state a linear pressure velocity relationship as long as inertia effects can be neglected. This is true as long as Re, based on a characteristic length-scale of the material is below unity.
The liquid flow and its pressure drop over the web and the actual thickness of the web were registered by a computer. The flow rate was measured by use of an electromagnetic flow meter DS21 made by ABB. This sensor measures a flow rate between 0 - 2 dm³/min, corresponding to a superficial flow velocity inside the cavity of 0 - 4.2 mm/s, with an accuracy of 1 % of the maximum reading. The pressure drop was measured with a differential pressure gauge, a Rosemount transducer model 1151 (range of 0-11 kPa 0.05 %) while the thickness of the pulp suspension was measured with a magnetostrictive position sensor, MTS sensors, a range of 0 - 0.3 m, ±0.08 mm. Note, the pressure drop over the dewatering plates was measured individually. It was found that the pressure drop throughout the plate in the flow range when measuring permeability was much smaller than the pressure drop throughout the material itself. However, the pressure drop was included in the permeability measurements. The temperature of the incoming fluid was measured with a PT 100 sensor with an accuracy of 1 %. The temperature was measured in order to adapt the correct viscosity when deriving the permeability of the porous material.
Figure 4-2. Schematic sketch of the measuring cell. The pressure transducers located as illustrated in the sketch measure the pressure drop of the liquid through the material. During the measurement, liquid is entering and leaving the cell through distribution plate that enabling an even flow field through the pulp suspension.

The pressure drop through a porous material, combined with the flow rate through it and its thickness, was as mentioned above measured during the measurements. A sensitivity analysis of how these parameters influenced the permeability of the pulp suspension resulted in a 1 to 1 relation, i.e. a 1 % variation in each of the mentioned variables gave a 1 % change in the measured permeability. Temperature, in turn, affected permeability indirectly by the viscosity of the fluid, and a first estimate is that an alteration of 1 % influenced permeability by 0.5 %. The total estimated error from the measurements conducted on 1 kg/m² was about 7 % at a porosity of 0.5.
4.2 Validation process of the permeability equipments

The experimental procedure when measuring the permeability is quite straightforward. In slow, viscous flow regimes the permeability is found by use of Darcy’s law. Typically any flow with a Re less than one is clearly laminar, and it would be valid to apply Darcy’s law. Experimental tests have shown that flow regimes with values of Re up to 10 may still be Darcian. Re for porous media flow is typically expressed as

\[ Re = \frac{\rho v d}{\mu} \]  

where \( \rho \) is the density of the fluid (units of mass per volume), \( v \) is the superficial velocity (not the pore velocity (with units of length per time), \( d \) in this case is representing the length scale in the system and is chosen to be the wood fiber diameter and \( \mu \) is the dynamic viscosity of the fluid.

4.2.1 Reference material

The procedure in how to determine the permeability of a porous material is quite straightforward. However, especially for a wood fiber suspension, where the fibers itself are compressible, the experiment has to be performed in a manner so that the fiber network is as close to homogenously distributed as possible. This indicates that along with the slow viscous flow that is stated by Darcy’s law the applied pressure drop needs to always be lower than the compressibility of the fiber suspension to maintain a homogenous fiber suspension. Small values in the signal from the sensors give a sensitive system towards surrounding disturbances. Consequently an incorrect placed pressure sensor will give an incorrect permeability of the material. To make sure that everything is in order, a reference material should be used in the experiments in order to validate that the equipment used is operating in a proper way.

To validate the permeability equipment measurements were carried out on a reference material being expandable polystyrene (EPS) spheres, with a mean diameter of 0.62 mm, delivered by the Finnish company StyroChem. This polymer is made of styrene containing pentane as a blowing agent. The EPS material has the following advantages when using it as a reference material: 1) Its permeability is in the same range as the fiber network at high porosity; 2) It is stable under testing conditions, and 3) its permeability can be estimated by analysis. An image analysis of the spheres was performed in order to estimate their diameter. The image analysis was conducted by examining the spheres in a microscope connected to the software “Image pro plus”. The analyzed image had a resolution of about 47 pixels per mm with a standard deviation measured to 0.131, Figure 4-3. The categorization of single spheres was accomplished by setting a threshold value for the roundness to 1.1 where the roundness is defined as:

\[ R_j = \frac{s_j^2}{4\pi A_j} \]  

where \( R_j \) is the roundness and \( A_j \) is the area of the jth sphere.
Figure 4-3. A part of the image used in the image analysis of the spheres. The bar in the pictures shows the length scale. Too dense area with spheres deviate from a spherical shape and are excluded from the analysis.

Here $S_j$ describes the perimeter and $A_j$ denotes the cross-sectional area of the spheres, respectively. Hence, for a perfect spherical particle, the roundness value is 1.0. By varying the roundness from 1.1 to 1.5, the mean diameter changed by only 0.8%, showing that the diameter of the spheres obtained is only marginally influenced by the choice of the threshold value.

Several methods were tested to determine the porosity of the EPS spheres under dry conditions. The porosity of a material is defined as the fraction of the bulk volume of the porous sample that is occupied by pore or void space. The methods used when estimating the porosity of the EPS material were based on the density method, which yields the total porosity. The density method depends on the ratio between the bulk density of the sample and the density of the solid particles. The density of the EPS spheres, $\rho_0$, was obtained from the supplier, 1010 kg/m$^3$ while the bulk density, $\rho_{bj}$, was determined by measuring the mass of the spheres used in the measurement.

The permeability of beds of spheres has been modeled by (Rumpf and Gupte 1971) yielding the following expression as long as Re, is less than 10:

$$k_j = \frac{d_j^2 \varepsilon_j^2}{5 \alpha S_j}. \quad (4-6)$$

where $d_j$ is the diameter of the spheres, $\varepsilon_j$ is the porosity of the spheres, and $S_j$ is a shape factor equal to one for a narrow distribution of diameters as is assumed for the EPS-spheres and equal to 1.05 for wider ones.
4.2.2 Permeability of the reference material

Measurements carried out in the out-of-plane set-up show that the apparent gas permeability of the EPS spheres, is dependent on Re, cf. Figure 4-4.

![Figure 4-4](image)

**Figure 4-4.** Non-dimensional apparent permeability of the EPS material. Triangles illustrate the permeability measurements conducted at too low Reynolds numbers with respects to the measuring system. The valid range of Darcy’s law is marked as circles. The diamonds denote a too high flow rate with inertia effects, cf (Dullien 1992).

At high Re, the reduction in apparent permeability is in accordance with the classic results obtained by (Rumpf and Gupte 1971), who attribute these phenomena to inertial effects, cf. Eq. (4-6). At low Re, the strong non-Darcian behavior can either be due to the Knudsen effect or may just be a result of erroneous values generated by the measuring system. The latter is a result of low flow rates with a corresponding low pressure drop. One consequence of a Knudsen flow is that the quantity of gas flowing through a capillary is larger than would be expected from the Poiseuille's formula at low pressure driven flows. This occurs for cases where the distance between the walls inside the porous material is similar to the free molecular path length of the flowing fluid. Since the main pores are of the order 1μm or larger, the Knutson effect is probably negligible for this case. Hence the limit of the measuring system as to pressure drop is defined in Figure 4-4. By performing measurements in the range Re = 3-12 the equipment can be validated by comparing results to theoretically derived expressions for permeability, Figure 4-5. One such expression that has been successfully validated with experiments is the one derived by (Rumpf and Gupte 1971) Eq. (4-6), see Figure 4-5 where also measurement from the wet permeability unit are presented.
Figure 4-5. Measured permeability results for EPS material in the permeability units. Verification of the units are found in the graph, diamonds represents the measurements in the liquid unit cell. Triangles are representing the air permeability conducted in the air unit cell and the theoretical model developed by (Rumpf and Gupte 1971), Eq. (4-6), (regression line).

Hence, measurement results performed in the two separate equipments follows Eq. (4-6) with a maximum deviation of 6% from the theoretical model. The experimental derived permeability in itself is dependent on two independent measurements: the porosity of the bed and the image analysis of the dimensions of the spheres. In addition, the total estimated error in these measurements was about 5% based on an analysis of the accuracy of the transducers and the geometry of the cell. It can thus, by all means, be concluded that both experimental set-ups performed excellent. This is of outmost importance for the rest of the discussion in this thesis.

4.3 Compressibility experiments

The pressure filtration cell is designed to measure the compression yield stress of the pulp suspension, Paper D.

4.3.1 Compressibility unit

The pressure filtration cell is designed to manage to compress pulp suspension by the use of a movable piston on which a dewatering filter plate was attached c.f. Figure 4-6. During the trial the pulp suspension was dewatered towards the filter and the consistency of the suspension was consequently increased. The cavity has a diameter of 100 mm and a maximum height of 42 mm. The pressure filtration cell was attached in a hydraulic press, MTS 312.21 load frame with a maximum load of ±100 kN, which corresponds to a specific surface pressure of 127 bar with a ±80 mm stroke. The data generated was recorded with a logger MTS FlexTest II with the MTS 793.00 system software ver. 3.3b, while the control monitoring program MTS Multipurpose
TestWare was used to collect the data, i.e. the actual position and the load applied to the static impermeable wall as a function of time.

![Diagram](image)

**Figure 4-6.**  A schematic sketch of the compressibility apparatus and principle movements.

The force generated to maintain constant velocity during dewatering is strongly dependent on the position of the piston, as well as velocity. Hence, it is extremely important to know the compliance of the total system, including the volume used for the sample, in order to describe the correct average solidity. This is particularly important towards the end of the compression trial, when the load is the largest while pulp suspension thickness is the lowest. The total applied force influences the surrounding system including the distance gauge, i.e. it is by all means necessary to take into account the compliance of the system. For example, the total load, in many cases, caused a strain in the system of nearly 0.2 mm, corresponding to the compliance of the system. Hence, it is important to adjust the signal from the position sensor in order to compensate for this effect.

### 4.4 Results and discussion/Material properties of wood fiber network

So far, focus has been put on the function of the set-ups used for the fundamental experiments. In what follows extracts from results generated with them.

#### 4.4.1 Permeability of fiber suspension

In order to evaluate the equipment for fiber mats, the gas permeability was measured as a function of time and Reynolds number. Regarding the function of time, the permeability was practically the same when the measurements were carried out with more than one year’s interval on two different batches. The batches were formed and degenerated at the specific day when the...
measurements were conducted, cf. Table 4-1. This indicates that the permeability equipment is stable, and the procedure of forming the fiber mat has been similarly performed, i.e. the systematical errors have the same influence on the permeability measurements on the different fiber mats. A direct comparison between the permeability measurements gives a maximum deviation of less than 8%. Unlike the permeability measurement on spheres, the permeability on fiber mats was unaffected by the Reynolds number in the measured flow interval, i.e. Darcy’s law is due to that valid. The Reynolds number for the gas flowing through the fiber mat was defined in a similar procedure as for the EPS material, (cf. Eq. 4-6). The characteristic length scale was set at the average fiber diameter obtained from the PQM measurement. The difference from the measurement with the spheres is that the pressure over the fiber network is relatively high also at low Re again indicating that the drift at low Re shown in Figure 4-4 is a result of the precision of the pressure transducers.

Table 4-1. The morphological data of the spruce fiber mats and the dryness value of the material at the time of the measurements. Batch 4 denotes the measurement conducted more than one year later compared to the other ones.

<table>
<thead>
<tr>
<th>Batch No.</th>
<th>Average outer diameter [μm]</th>
<th>Average fiber length [mm]</th>
<th>Coarseness value [mg/m]</th>
<th>Dryness [kg/kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>29.0</td>
<td>1.80</td>
<td>0.50</td>
<td>0.93</td>
</tr>
<tr>
<td>2</td>
<td>29.3</td>
<td>1.84</td>
<td>0.43</td>
<td>0.93</td>
</tr>
<tr>
<td>3</td>
<td>28.5</td>
<td>1.85</td>
<td>0.37</td>
<td>0.93</td>
</tr>
<tr>
<td>4</td>
<td>32.18</td>
<td>2.14</td>
<td>0.64</td>
<td>0.91</td>
</tr>
</tbody>
</table>

Results of the measured permeability for the fiber mat in the in-plane and in the out-of-plane direction are given in Figure 4-7. It is shown that the permeability of the spruce fiber mats has an anisotropic behavior at low porosity as outlined by (Hakansson, Toll et al. 2005) for a similar material. In order to find the level of anisotropy, the measured permeability was fitted to the following empirical equation, similar to the equation found by (Koponen 1998) for pulp suspensions:

\[
k = d_f \frac{B_1}{(\phi_2/\phi_1 - 1)\phi_2^2}, \tag{4-7}
\]

where \(B_1, B_2\) and \(B_3\) are empirical constants for the wood fiber mats, Table 4-2 \(\phi\) is the solidity of the fiber mat, and \(d_f\) is the diameter of the fiber. The result is that there is an anisotropy already at the lowest porosity in that sense that the in-plane permeability is lower, see the right-hand axis in Figure 4-7. However as the mat is compressed the in-plane permeability becomes higher and the anisotropy reaches a value of about 40%. A re-arranged fiber network from a random to an oriented structure could explain the differences in the results. If so, the differences should go towards an asymptotic relationship since the permeability is solely dependent on the geometry of
the material (Hakansson, Toll et al. 2005). The measurement at high porosity should give the same permeability since the fiber mat is formed in a procedure where the fibers are more or less randomized. Even though the forming of the fiber mat was performed in a similar procedure, an orientation could be introduced, since the first permeability value was determined at a lower porosity level than the actual forming one. If so, the differences should go towards an asymptotic relationship since the permeability is solely dependent on the geometry of the material (Scheidegger 1974).

Figure 4-7. Non-dimensional plot of measured permeability on spruce fiber mats. Data points are from measurement performed in in-plane and out-of-plane direction. The permeability model described in Eq. (4-7) has been used to determine the percentage difference between the out-of-plane and in-plane measurements. The empirical constants are given in Table 4-2.

Table 4-2. The empirical constants for the permeability model valid for the fiber mats and the $R^2$ value of the fitted models.

<table>
<thead>
<tr>
<th>Dry Permeability model</th>
<th>$B_1$</th>
<th>$B_2$</th>
<th>$B_3$</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spruce fiber out-of-plane direction</td>
<td>0.148</td>
<td>8.168</td>
<td>1.691</td>
<td>0.948</td>
</tr>
<tr>
<td>Spruce fiber in-plane direction</td>
<td>0.414</td>
<td>15.259</td>
<td>0.981</td>
<td>0.979</td>
</tr>
</tbody>
</table>
4.4.2 Permeability of pulp suspension

The geometrical parameters of the fibers in the pulp suspensions were measured with the commercial image processing equipment (kajaaniFiberlab 2004), Table 4-3. The resolution of the image obtained was about 1 μm per pixel for determining the fiber width and 10 μm per pixel for determining the length of the fiber. In addition, the coarseness value, i.e. weight per meter fiber was estimated. This procedure was repeated after the permeability measurements and no significant change in geometrical parameters could be determined.

Table 4-3. Fiber properties, from the kajaaniFiberLab equipment.

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Average fiber width, [μm]</th>
<th>Length weighted average fiber length, [mm]</th>
<th>Weight weighted average fiber length, [mm]</th>
<th>Arithmetic average fiber length, [mm]</th>
<th>Coarseness value, [mg/m]</th>
<th>Fiber Curl, [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>24.40</td>
<td>2.25</td>
<td>2.78</td>
<td>1.50</td>
<td>0.159</td>
<td>16.3</td>
</tr>
<tr>
<td>2</td>
<td>26.15</td>
<td>2.26</td>
<td>2.85</td>
<td>1.44</td>
<td>0.146</td>
<td>12.2</td>
</tr>
<tr>
<td>3</td>
<td>25.95</td>
<td>2.25</td>
<td>2.82</td>
<td>1.45</td>
<td>0.143</td>
<td>13.5</td>
</tr>
<tr>
<td>4</td>
<td>16.10</td>
<td>0.91</td>
<td>1.06</td>
<td>0.76</td>
<td>0.069</td>
<td>13.7</td>
</tr>
<tr>
<td>5</td>
<td>15.60</td>
<td>0.80</td>
<td>0.88</td>
<td>0.715</td>
<td>0.059</td>
<td>17.8</td>
</tr>
<tr>
<td>6</td>
<td>15.60</td>
<td>0.80</td>
<td>0.88</td>
<td>0.715</td>
<td>0.060</td>
<td>17.5</td>
</tr>
</tbody>
</table>

The fiber length is defined as the true length of the fiber along the centerline.

Since the permeability of the pulp suspension is strongly dependent on solidity, hence permeability measurements were performed on different solidity values for the pulp suspension. This procedure was repeated until the lowest possible volume of the cavity was reached, with respect to the limit of the pressure transducer or until the maximum load from the hydraulic press that was used to compress the suspension was achieved.
All pulps were re-pulped and prepared according to SS-EN ISO 5263-1:2004. The amount of pulp corresponding to the desired surface weight was placed into the measuring cavity. The pulp suspension was poured into the measuring volume with a consistency by mass of 1% to eliminate the amount of trapped air inside. For some cases the differential pressure sensor did not reach its zero value, indicating trapped air inside the suspension. Then a flow rate was applied through the suspension until equilibrium at zero was reached. After that the suspension was slowly compressed to the desired start consistency of about 5%.

In the experiments performed on pulp the Re was in the order of 0.0001. By integrating Eq. (4-1) in the flow direction and by assuming a homogeneous porosity profile the permeability of the pulp suspension was determined. Measurements were conducted on four pulps: two bleached birch sulphate pulps, one bleached pine sulphate pulp and one unbleached spruce sulphite pulp. A homogenous suspension was ensured by mixing in a STAMO mixer for two minutes. A fiber bed was formed by filtration of a very dilute pulp suspension (< 0.1 %). The fiber web was dried to 115 °C for about 24h and weighed after each experiment. The compressibility and permeability were then determined at successively increasing compacting pressures in order to avoid hysteresis of creep effects. Fresh pulp samples were used in each experiment. The accuracy of the rotameter, temperature control and pressure measurement was 1 %, 0.5 % and 0.5 % respectively. One result was that the pressure drop was time dependent. This was explained in the following way; during permeability measurement, the flow speed is slow, i.e. it takes about 30 minutes just to exchange the water inside the mould, the fiber itself works like an impulse damper. Hence, before any permeability measurements can be performed the pressure drop and the flow speed must be at constant level.

A variation in Re showed only a small variation in permeability that most likely originates from the measuring system in a similar manner as for the gas permeability measurements. According to Darcy's law, Eq. (4-8), permeability should be independent on the basis weight. However for small basis weights a slight deviation from true pulp thickness due to stochastic variations strongly influenced the calculated porosity, especially at small thicknesses. This is illustrated in Figure 4-8, and could be one explanation for the large scattering effect most apparent at low porosities. The measurements performed on higher basis weights (2 kg/m²) give slightly lower variation. Similar results were found for BHK and SBSK pulps. The empirically determined constants for the permeability model, Eq. (2-3) are given in Table 4-4.
Figure 4-8. Measured non-dimensional permeability of SBBSK pulps at different basis weights. The squares and triangles denote basis weights of 1 and 2 kg/m² respectively.

Table 4-4. The empirically determined constants of the tested pulps for the permeability model.

<table>
<thead>
<tr>
<th>Pulps</th>
<th>C₁</th>
<th>C₂</th>
<th>S₀</th>
<th>R²</th>
<th>εₘₐₓ</th>
<th>εₘᵟᵟn</th>
</tr>
</thead>
<tbody>
<tr>
<td>SBBSK</td>
<td>234.6</td>
<td>3389.0</td>
<td>1.50E+05</td>
<td>0.934</td>
<td>0.98</td>
<td>0.50</td>
</tr>
<tr>
<td>SBSK</td>
<td>174.7</td>
<td>8718.0</td>
<td>1.54E+05</td>
<td>0.963</td>
<td>0.98</td>
<td>0.75</td>
</tr>
<tr>
<td>BMTH</td>
<td>168.9</td>
<td>2429.2</td>
<td>2.48E+05</td>
<td>0.990</td>
<td>0.98</td>
<td>0.63</td>
</tr>
<tr>
<td>BHK</td>
<td>189.4</td>
<td>1040.8</td>
<td>2.56E+05</td>
<td>0.966</td>
<td>0.96</td>
<td>0.67</td>
</tr>
</tbody>
</table>

The permeability results of the different types of pulp suspensions revealed that the permeability of the Hardwood, BHK and BMTH pulps was higher overall than the Softwood, SBSK and SBBSK pulps especially at low porosities even though the diameter of the hardwood fiber was smaller, illustrated in Figure 4-9 where the results performed by (Lindsay 1990) are plotted as regression lines.
4.4.3 Compressibility of pulp suspension

The slurry was formed manually with a spoon in the cavity, Figure 4-6. The spoon was used to flatten and distribute the pulp as evenly as possible onto the filtration plate. The filtration plate had an open area to flow of 19% in the form of a number of holes, each with a diameter of 1 mm. The pulp suspension used in the experiments was a Scandinavian fully bleached baled softwood pulp from the Östrand mill in Sundsvall, Sweden. The pulp suspension was disintegrated using a standardized method according to ISO5263-1:2004.

The experiments were performed by applying a constant pressure filtration velocity on the movable piston. This was continued until maximum load of the press was achieved, i.e. 100 kN. This was performed several times for each pulp suspension with speeds from a few mm/s up to about 8 mm/s in order to investigate the influence of pressure filtration velocity on the dewatering ability of the pulp suspension. The initial properties of the pulp suspension and experimental settings are shown in Table 4-5.
Table 4-5. Experimental conditions. The initial concentration by weight was aimed at 5%. The pulp was a baled and fully bleached pulp from the Östrand mill in Sundsvall, Sweden.

<table>
<thead>
<tr>
<th>Test no.</th>
<th>Pressure filtration speed, ([\text{m/s}])</th>
<th>Basis Weight ([\text{kg/m}^2])</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.97E-6</td>
<td>1.02</td>
</tr>
<tr>
<td>2</td>
<td>2.49E-4</td>
<td>2.04</td>
</tr>
<tr>
<td>3</td>
<td>4.99E-4</td>
<td>2.01</td>
</tr>
<tr>
<td>4</td>
<td>9.95E-4</td>
<td>2.04</td>
</tr>
<tr>
<td>5</td>
<td>1.99E-3</td>
<td>2.08</td>
</tr>
<tr>
<td>6</td>
<td>3.99E-3</td>
<td>2.05</td>
</tr>
<tr>
<td>7</td>
<td>7.98E-3</td>
<td>1.94</td>
</tr>
</tbody>
</table>

During the pressure filtration experiments the applied pressure is as previously mentioned split between the fluid and solid phase, (Terzaghi and Peck 1948). The contribution of respectively phase during filtration can be estimated individually. At low pressure gradients, the fluid pressure can be determined by use of Darcy’s law, Eq. (4-1). The challenge when determining the compressibility of the fiber suspension is to exclude the fluid forces that act within the suspension during filtration. This is guaranteed by applying a very slow pressure filtration rate, meaning that the fluid pressure is magnitudes lower than the compressive yield stress or fiber network strength. This implies that the estimated parameter is solely related towards the fiber network itself.

The pressure as a function of solidity was derived for quasi-static conditions and experimental data was fitted to Eq. (2-4) resulting in an \(R^2\) value of 0.97 where the deviation mainly occurred at high pressures. In order to obtain better conformity, the data was fitted to the following expression, see solid line in Figure 4-10.

\[
p_s = \frac{E_1 \phi E_2}{(1-\phi)E_3}
\]

(4-8)

where \(E_1\), \(E_2\), and \(E_3\) are adjusted for this specific pulp suspension to 3.11e6 [Pa], 2.56 and 3.18, respectively and \(\phi\) denotes solidity of the pulp suspension. Notice that if \(E_1\) and \(\phi\) are small, Eq. (2-4) and Eq. (4-8) are practically equal. However, in the current case, the constants resulting from the curve fitted to an \(R^2\) value of 0.99 imply that \(E_3\) attains a value close to 3, thus indicating the need to take into account additional mechanisms to those modeled by (Toll 1998). It is also obvious that the higher the velocities of the piston, the higher the pressure generated at a given porosity, compare Table 4-5 and Figure 4-10.
Figure 4-10. Results of the total applied pressure in the measurements. The required pressure increases with pressure filtration velocity at all porosities.
5. Case Studies

Two cases have been studied. The first case relates to the flow taking place when de-airing a wood fiber network in a belt press during manufacturing of medium density fiberboards. In the second case dewatering of a wood fiber suspension during a one-dimensional pressure filtration is considered. In the first case a low viscous fluid penetrates a rather dense and thus stiff fiber network, while in the second case a relatively high viscous liquid penetrates a compliant fiber network.

5.1 Continuous felt press

In the beginning of the final phase of the manufacturing of dry-formed fiberboards, a fairly thick network of loosely entangled wood fibers is compressed to often less than a tenth of its original thickness in a continuous belt press. During this densification the fibers are subjected to stresses generated by the air leaving the network. These stresses are often balanced by the network strength but if the speed of the fiber network through the belt becomes too high the fiber network will burst and the process will be stopped.

5.1.1 Modeling

The flow presented above has some similarities to the flow that takes place in a press nip during dewatering of paper which has been modeled in a number of cases (Wahlström 1960; Asklöf, Larsson et al. 1964; Kershaw 1972; El-Hosseiny 1991). Most of these felt models are based on Darcy’s law and several are one-dimensional although there are examples of models handling two-dimensional multiphase flow (Kataja, Hiltunen et al. 1992; Zahrai, Bark et al. 1997). High pressure gradients in the fluid phase may result in densification of the fiber mat, (Zhu, Pelton et al. 1995; Lobosco, Norman et al. 2005). This is, however, of less importance for flow of a low viscous fluid.

In order to clarify the mechanisms taking place during the formation of fiberboards a semi-analytical model was developed in Paper B. The technique is similar to that used for felts but the geometry, the fluid, and the boundary conditions differ. By applying the following assumptions:

Figure 5-1. Simplified 2D-geometry of belt press.
the belt press can be mimicked by the geometry described in Figure 5-1,

the flow of air follows Darcy’s law,

the angle $\alpha$ is small and the flow through the side, top, and bottom walls can be neglected, and the flow is approximated to be in one direction only while keeping continuity, lubrication approximation,

the speed of the air and the fiber bed are equal when $x = L$,

the fiber volume fraction is only a function of $x$,

the volume and density of the fibers and the resin are constant,

the temperature is constant and no gas is generated within the press.

and doing some analysis, the following expression results

$$-2\mu v_r \left( \frac{h_1 - h_2}{L} \right) = \frac{1}{\rho} \frac{\partial (k \phi \rho^2 \frac{\partial}{\partial x})}{\partial x}.$$  \hfill (5-1)

In this equation $v_r$ is the velocity of the belt and the geometrical variables are defined in Figure 5.1. The term on the left-hand side is independent of $x$ while all variables on the right-hand are functions of $x$. At this point it is possible to choose any model for the permeability. In the analysis presented in Paper B, the Cozeny-Karman equation is applied being the most frequently used model although it does not have proper micromechanical basis. It has, however, turned out that it can describe $k$ for a number of materials as a function of the solidity, $\phi$, fiber diameter $d_f$, and a non-dimensional shape constant $g$ in the following way:

$$k = \frac{(1-\phi)^3}{\phi^2} g \left( \frac{d_f}{2} \right)^2 = \frac{(1-\phi)^3}{\phi^2} C.$$  \hfill (5-2)

The constant $C$, having dimension [m$^2$], is introduced for the purpose of simplifying discussion. The fiber volume fraction may in turn be expressed in terms of the basis weight, $w$, [kg/m$^2$], the density of the fibers, $\rho_f$, [kg/m$^3$], and the height of the press, $h$, [m] according to:

$$\phi = \frac{w}{h \rho_f}.$$  \hfill (5-3)

which combined with Eq. (5-1) result in

$$-2\mu v_r \rho_f \left( \frac{h_1}{h_2} \right) \frac{1}{w} \frac{1}{L} = \frac{1}{h_1 \rho} \frac{\partial \left( \frac{h \rho_f}{w} - 1 \right)^2 \rho^2 \frac{\partial}{\partial x}}{\partial x}.$$  \hfill (5-4)
It can now be seen that changes to the parameters in the ratios on the left-hand side only affect the result if each ratio, except \( h_1 \), is changed. This height sets the scale of the problem and appears as well as a sole term in the right-hand side of the equation. Hence, according to Eq. (5-4), the pressure field within the press will be unaffected as long as the following equalities are satisfied:

\[
\left(1 - \frac{h_1}{h_i}\right) \left[\frac{\mu \nu}{c_l}\right] = \left(1 - \frac{h_1}{h_i}\right) \left[\frac{\mu \nu}{c_l}\right]^T
\]

and

\[
\left[\frac{p_r}{w}\right]^I = \left[\frac{p_r}{w}\right]^T,
\]

where the superscripts \( I \) and \( T \) denote the initial and tailored cases, respectively. Consequently, it is possible to increase the velocity of the belts as long as the length of the press is increased, or viscosity of the penetrating fluid is decreased correspondingly. Furthermore, the basis weight of the fiber mat can be changed as long as it is matched with an equal change in the density of the fibers. Hence a couple of rules of thumbs are presented showing how to match different variables to keep a constant force on the fiber network.

The pressure field given by Eqs. 5-1-5.3 is also solved numerically in Paper B with material properties from Paper A. A main result was that minor variations in the pressure at the nip may result in huge differences in the pressure at the entrance of the press. Hence, natural variations in the permeability at the nip may give a substantial pulsating flow at the end, possibly enhancing the risk for a fatal failure of the fiber mat.

### 5.1.2 Validation

The model presented above was validated by detailed pressure measurement performed in field on a full-scale belt press, Paper B. The material was a poplar fiber mat with an initial moisture content of about 10 % and the pressure was monitored with a system called PressMan Contipro that consists of a logger and a probe. The logger can store up to 1022 data readings, and the logging frequency can arbitrarily be chosen in the interval 0.1-10 Hz. The dimensions of the logger used were: width 48 mm, length 385 mm, and thickness 9.5 mm and the probe was 850 mm long, see Figure 5-2.
Figure 5-2.  Schematic sketch of the PressMan equipment. The logger is attached to the center of the edge of the fiber mat and follows the fiber mat through the entire press.

The geometry of the full-scale press is similar to the geometry of the press used to derive Eq. (5-4) but differed in detailed geometry; cf. Figure 5-1 and Figure 5-3.

Figure 5-3.  A sketch of the full-scale Continuous press. The simulations were conducted from the inlet up to frame 3. The dimensions are in mm.

The procedure for each measurement was that at the entrance of the press, the probe tip was placed close to the center of the mat in terms of width and the horizontal direction. The logger was then attached to the probe, and the whole system was allowed to follow the fiber mat through the entire press. The result was that the pressure increased nearly linearly up to frame 2 after which its dependency accelerated; cf. Figure 5-3 and Figure 5-5. To compare experimental results with simulated ones it is necessary to know the permeability of the fiber bed moving through the
press. The permeability can be obtained as a function of fiber mat density by using the system presented and validated in Paper A. In order to derive the material variable $C$ in Eq. 5-2, from such measurements, the relation between packing density and the fiber wall density of the hollow and encapsulated fibers must be known. Since wood fibers are porous, as shown in Figure 5-4., their bulk density can increase as the fiber mat is compressed.

![Figure 5-4. Schematic picture displaying fiber geometry of the internal structure of pinewood chip in cross-section. Published with permission from Staffan Palovaara, SCA Research.](image)

It was therefore in place to compute $C$ for a number of values of the fiber density all being located between the bulk density of an non-deformed fiber of about 450 kg/m$^3$ and the density of a fiber wall, 1550 kg/m$^3$, Table 5-1.

<table>
<thead>
<tr>
<th>$\rho_f$ [kg/m$^3$]</th>
<th>$C \times 10^{12}$ [m$^2$]</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>800</td>
<td>3.78</td>
<td>0.98</td>
</tr>
<tr>
<td>1000</td>
<td>1.78</td>
<td>0.95</td>
</tr>
<tr>
<td>1200</td>
<td>1.03</td>
<td>0.92</td>
</tr>
<tr>
<td>1400</td>
<td>0.67</td>
<td>0.90</td>
</tr>
</tbody>
</table>

By using the processing variables in Table 5-1, and assuming atmospheric pressure 0.1 MPa at the inlet of the model the pressure distribution was derived by usage of Eq. (5-4). The result was that the model proposed captures the central characteristics of the pressure inside the fiber network but, that it gives considerably higher values than what were obtained from experiments, regardless of the density of the fibers, see Figure 5-5.
There are at least three major reasons for this. The first explanation is simply that, in reality, air can escape through the vertical sides of the press. Second, the belts have a higher temperature than the fiber mat. This may result in a gradient in compliance with the fiber mat and possibly a larger densification in the areas closest to the belts. If this is true, the permeability will be considerably higher in the core of the fiber mat resulting in an overall higher relative flow also in the main flow direction (Bear 1972). Third, it is likely that $\rho_f$ will increase with $\phi$, that is that the soft and hollow wood fibers will deform. The open spaces between the fibers will therefore not be condensed as fast as predicted for solid fibers. This may result in a lower reduction in permeability than what is obtained from the curve fit to the measured data, which was done for rather modest fiber volume fractions. The last two reasons imply that the permeability is generally higher than that obtained from the permeability measurements. Consequently, it is reasonable to set higher values for $C$ than that obtained from the permeability measurements. This is demonstrated by increasing the value of this parameter by five and ten times for $\rho_f = 1000$ kg/m$^3$. The modeled pressure then approaches the experimentally derived ones, see Figure 5-6. Otherwise, modeling of the full 3D-flow, adding the temperature field, and better describing the density of the fibers would sharpen our predictions, and is a matter for further research.
Figure 5-6. Comparison between experiments and pressure distribution when the fitting parameter is increased according to the relationships stated in the legend.

5.2 Deformation of fiber network in wet pressing

One explanation for the disagreement between theory and experiments in the former section on the flow field study in a continuous press was that the material in the compression direction was not uniformly distributed. In these cases the temperature from its boundary seemed to influence the solidity gradient. However, in wet pressing the forces from the liquid water on the fiber is magnitudes higher as compare with air at the same time as the geometry differs. A non uniform concentration of the fibers is therefore more readily due to pressure concentrations in the water than due to variation in temperature. The exact mechanism by which the network deforms under load still remains an open question. Hence, a study was performed in order to study the interparticle interaction in a suspension and the pressure on them. One of the remaining difficulties with such suspensions is that during filtration, densification of the suspension may be in the form of a reduction of the interparticle spacing as well as by deformation of the individual particles themselves in a similar manner as indicated for dry wood fiber networks. This leads to an additional complication in describing the local particle pressure as the compression is governed by mechanisms which act at on different geometrical and time scales.

5.2.1 Modeling

The advantage of the pressure filtration, when it comes to modeling, is that the main flow and the compression take place in one-direction. It is therefore highly relevant to apply a one-dimensional model as done in Paper E for a cylindrical filter press using a volume averaged Eulerian-Eularian approach. The analysis presented follows closely previous filtration models for a colloidal stable suspension, e.g. (Landman, Sirakof et al. 1991), but an additional kinetic
expression to describe the kinetics of consolidation was included. This expression is similar in form to one posed originally by (Buscall and White 1987) for consolidating colloidal particles settling in a centrifuge and like (Buscall and White 1987) a function is introduced, termed the "dynamic compressibility" which in effect describes a lag between the application of a force and the response of the network. The analysis is limited to estimating the pressure $\sigma(t)$ required to maintain a constant filtration rate $u_c$ of a dilute papermaking suspension at an initial solidity of $\phi_0$.

Now, consider a filtration event in which a filter is located at $x=0$ and the domain extends upwards to a piston located at $x=h(t)$; $h_o$ is the initial height illustrated in Figure 5-7. The suspension fills this domain and is drained under the pressure generated as the piston moves towards the filter. Plug flow is assumed and solidity of the suspension does not vary significantly over its cross-section. Conservation of particles and fluid masses requires that

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho U) = 0 \quad (5-7)$$

$$\frac{\partial}{\partial t} \left[ \phi \right] + \nabla \cdot \left[ (I - \phi) F \right] = 0 \quad (5-8)$$

where $U$ and $F$ are the velocities (vector quantities) of the particles and fluid. The volume fraction (or solidity) of the particle phase is denoted by $\phi$ and is defined as the ratio of volume of the fibers to the total volume of the suspension. In the force balance equations, as argued by (Landman, Sirakof et al. 1991) essentially the hydrodynamic drag forces will balance the pressure gradients and as a result, the equations of motion reduce to

![Figure 5-7. A sketch of the pressure filtration cell used in the filtration events.](image-url)
\[
0 = -\frac{\partial p}{\partial x} \mathbf{\hat{x}} - \frac{\partial p_s}{\partial x} \mathbf{\hat{x}} - \frac{1 - \Phi}{k(\Phi)} (U - F) \quad \text{(5-9)}
\]

\[
0 = -(1 - \Phi) \frac{\partial p}{\partial x} \mathbf{\hat{x}} - \frac{1 - \Phi}{k(\Phi)} (U - F) \quad \text{(5-10)}
\]

where \( p \) is the fluid pressure; \( \mu \) is the viscosity of the fluid; \( p_s \) is the solid network pressure and \( k(\Phi) \) is the permeability of the particle network a property well described in this thesis, in the force balance equations the inertial, gravitational, and shear stress terms are neglected which is justified in Paper E.

Now consider that the fiber network requires time to respond to changes in an external load as indicated in Paper D with the scenario that this lag results from fluid being expressed from the spaces within the wood fibers. In Paper E this process is studied by use of an energy conservation equation. It is assumed that the energy dissipation on the network is equal to the viscous dissipation generated by fluid flowing through a small pore. The basis for this argument is given by (Buscall and White 1987) and the wording and logic presented below follows this reference quite closely.

To begin with, consider a volume element \( V \) of a networked suspension at a volume fraction \( \Phi \) subject to an external network load \( p_n \) large enough to cause collapse of the local network. The network itself is capable of resisting this pressure by generating internally an opposing pressure \( p_y(\Phi) \). The net work done in increasing the volume fraction by an amount \( d\Phi \) is

\[
dW = - \left( p_n - p_y(\Phi) \right) dV = V \left( p_n - p_y(\Phi) \right) \frac{d\Phi}{\Phi} \quad \text{(5-11)}
\]

and the rate of doing work on the system can be estimated using

\[
\frac{dW}{dt} = \frac{V}{\Phi} \left( p_n - p_y(\Phi) \right) \frac{d\Phi}{dt} \quad \text{(5-12)}
\]

It is now assumed that most of this work is dissipated in the fluid as it flows through a number of pores of length \( \ell \) and radius \( r_0 \). Further it was assumed a fully developed Hagen-Poiseuille flow in the pore in which the fluid is driven by the pressure gradient \( \tilde{p} = \left( p_n - p_y(\Phi) \right) / \ell \). Hence, the velocity field \( \mathbf{v} \) in a single pore is given by

\[
\mathbf{v} = \frac{\tilde{p}}{2 \mu} (r_0^2 - r^2) \quad \text{(5-13)}
\]

The viscous dissipation rate per unit volume at the wall of the pore is \( \mu (dv/dr)^2 \) and the total dissipation rate in the volume element is therefore
Equating the viscous dissipation rate to the rate of doing work on the system Eq. (5-12) yields

$$\frac{d\Phi}{dt} \approx \frac{1}{\lambda(\phi)} \left( p_s - p_x(\phi) \right)$$

(5-15)

where

$$\lambda(\phi) = \frac{4\mu c^2}{r_0^2}$$

(5-16)

At this point it is necessarily to make further assumptions regarding the dimensions of the pore. As permeability in a very broad sense is a measure of the characteristic area of a pore, we set $r_0^2 \sim k(\phi)$. The characteristic length of the pore is difficult to ascertain and as a first approximation we argue that this term must be related to some characteristic length of the particle itself, i.e. its length or cell wall thickness.

The argument presented here indicates that when the characteristic radius of the pore is small in comparison to the path length of the fluid, i.e. $k(\phi)/r_0^2 \rightarrow 0$, the dynamic compressibility function becomes very large. This indicates that the network responds very slowly to changes in the applied force. This is the case I feel represents in the pressure filtration of wood fiber suspensions, Paper D. In the opposite sense, when the path length is very small in comparison radius of the pore, the dynamic compressibility function is very small implying that $p_s \approx p_x(\phi)$. Physically this is interpreted to mean that the suspension densifies immediately with an externally applied force. This scenario was the case originally considered by (Buscall and White 1987) where colloidal stable suspensions of "hard" particles were filtered under pressure. Although the true functional form of the dynamic compressibility is difficult to ascertain apriori, in this section Eq. (5-16) is evaluated, by solving Eq. (5-20) through (5-22), and by comparing the solution to experimental data.

The governing equations to solve is described below

$$\frac{d\Phi}{dt} + \frac{\partial}{\partial x} (\Phi U)$$

(5-17)

$$\frac{\partial p_s}{\partial x} = \frac{\mu}{(\phi - \phi_0)k(\phi)} (U - U_F)$$

(5-18)

$$\frac{\partial u}{\partial x} = \frac{1}{\lambda(\phi)} \left( p_s - p_x(\phi) \right)$$

(5-19)

All that remains at this point are the initial and boundary conditions. At time $t=0$, it is assumed that $\phi$ is constant throughout the cylinder. This implies that
\[ \phi(x,0) = \phi_0 \] 

(5-20)

The particle velocity satisfies

\[ U(0,t) = 0 \] 

(5-21)

\[ U(h(t),t) = U_F \] 

(5-22)

since no particles move through the filter membrane at \( x=0 \) and the particles move with the velocity of the piston at \( x=h(t) \), illustrated in Figure 5-7. In addition it is obvious that the network stress \( p_n \) must equal the applied pressure \( \sigma(t) \) at \( x=0 \), as long as the flow resistance of the filter membrane can be considered to be magnitude smaller. Details of this latter expression are explained in further detail by (Landman, Sirakof et al. 1991). In essence, this expression stems from the Terzaghis principle, (Terzaghi and Peck 1948), that the sum of the fluid and network pressures are equal to the applied pressure at every elevation in the device. More details about how to treat the equations in the model is found in Paper E.

5.2.2 Solid pressure experiments

Experiments were conducted in which the force required to dewater a papermaking fiber suspension was measured at a constant displacement rate as described in section 4.6. All experiments were performed on a Scandinavian fully bleached baled softwood pulp, SBBSK, see Table 4-3. The pulp suspension was disintegrated and filled into the cavity of the apparatus, see section 4.5. The cavity had a diameter of 0.1 m and a maximum pulp height of 42 mm. A hydraulic piston was attached to an MTS 312.21 load frame with a maximum load of 100 kN with a 80 mm stroke. A constant pressure filtration velocity was applied to the permeable piston until maximum load of the press was achieved. This was performed several times with speeds from a few mm/s up to about 8 mm/s in order to investigate the influence of pressure filtration velocity on the dewatering ability of the pulp suspension, see Table 5-2.
Table 5-2. The experimental condition tested.

<table>
<thead>
<tr>
<th></th>
<th>$U_f$ (mm/s)</th>
<th>$\phi$</th>
<th>$h_0$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>0.25</td>
<td>0.06</td>
<td>20.1</td>
</tr>
<tr>
<td>b</td>
<td>0.50</td>
<td>0.06</td>
<td>20.5</td>
</tr>
<tr>
<td>c</td>
<td>2.0</td>
<td>0.06</td>
<td>23.1</td>
</tr>
<tr>
<td>d</td>
<td>2.0</td>
<td>0.06</td>
<td>22.3</td>
</tr>
<tr>
<td>e</td>
<td>4.0</td>
<td>0.05</td>
<td>26.6</td>
</tr>
<tr>
<td>f</td>
<td>8.0</td>
<td>0.05</td>
<td>27.1</td>
</tr>
</tbody>
</table>

In order to be able to compare the model to these experiments, two experimentally determined functions are required. The compressive yield stress $p_y$ has been measured according to Eq. (4-8), where $E_1=3.1$ MPa, $E_2=2.6$, and $E_3=3.2$. The permeability of the fiber network where Eq. (2-3) is fitted to experimental data to yield the values presented in Table 4-4.

5.2.3 Results and Discussion

To start with the equations are solved numerically by assuming that there is no "lag" between the application of force and densification of the network, i.e. $\ell = 0$. The implications of this assumption are that densification of fiber network occurs instantaneously as the pore length is small and $P_s$ is always equals the equilibrium value of $p_y$. It should be noted that no fitting parameters are introduced. The first observation is that the difference between the model and the experiments increases with increasing rate of the piston, see Figure 5-8. In fact, the error is as large as 8 mm/s, see Figure 5-8f. The second observation is that the model under predicts the experimental results consistently. Clearly under this assumption, the model performs quite poorly.
Figure 5-8. A comparison of the experimental data (markers) with the prediction (dashed line) given for the condition $\ell = 0$. The data is shown in six subplots representing each of the experimental conditions: (a) $u_f = 0.25$ mm/s; (b) $u_f = 0.50$ mm/s; (c) $u_f = 1.0$ mm/s; (d) $u_f = 2.0$ mm/s; (e) $u_f = 4.0$ mm/s; and (f) $u_f = 8.0$ mm/s.

In a second stage the governing equations are solved by setting $\ell$ equal to twice the length of a typical fiber. A comparison of the experimentally measured pressure profile with the prediction is given in Figure 5-9. It is now evident that the behavior of the model resembles the experimental data quite well.
Figure 5-9. A comparison of the experimental data (markers) with the prediction (dashed line) given with the assumption for the form of $l$ equal twice the length of a fiber. The data is shown in six subplots representing each of the experimental conditions: (a) $u_F = 0.25$ mm/s; (b) $u_F = 0.50$ mm/s; (c) $u_F = 1.0$ mm/s; (d) $u_F = 2.0$ mm/s; (e) $u_F = 4.0$ mm/s; and (f) $u_F = 8.0$ mm/s.

5.3 Visualization Experiments of Pressure filtration

Visualization experiments were performed in order to increase the insight in the pressure filtration of a network consisted of papermaking fibers and to verify the validity of the numerical model. To fully describe the behavior of how the papermaking fibers move during pressure filtration one need not only to capture the applied pressure onto the structure, another important parameter to describe is the solidity profile. To describe the applied pressure the solidity profile might take a variety of shapes. In order to study the solidity profile in a pressure filtration trial a visualization study was performed by use of a technique that traces the particle inside the cell. In this study we traced the deformation of the network, with “Positron Emission Tomography” (PET). This is not a new technique in itself but it has only rarely been used for industrial applications, (Khalili, Basu et al. 1998; Young, Martinez et al. 2006; Heath, Olson et al. 2007). As compared to other techniques for flow visualization inside a porous media, PET has two main advantages: The porous medium in its original form can be directly put inside the scanning volume of the tomography. PET is able to provide full three-dimensional pictures of the passive scalar, in the present case a radioactive tracer, distribution inside the porous material. The exact mechanics by which the network deforms under load remains as an open question. One likely scenario is, however, that during uniaxial compression there is initially a reduction in the
interparticle spacing and an increase in the number of intra-fiber contacts. At some degree of compression, the number of fibers in contact is such that further compression can only occur by bending of the fibers and deformation of the individual fibers themselves. For wood fibers this will imply a collapse of the fiber wall closing the hollow central region of the fiber. If saturated, the rate of collapse of the cell wall is dictated by the rate by which the fluid can drain from the intra-fibrillar region through the inter-fibrillar space illustrated in Figure 5-10. The technique has a potential to allow us to gain insight in how the movements of fibers occur during pressure filtration. In the present work the focus was not primarily aiming at detecting the movements and deformations of individual fibers inside the suspension but rather displaying gradients in the fiber volume fraction.

The experiments were conducted on a fiber suspension doped with a small part of radioactive fibers. This mixture was put into a specially designed pressure filtration unit that was placed within the x-ray field of the positron emission tomography. A detailed description of the pressure filtration unit, the positron emission tomography, and the experimental procedure will now follow.

![Figure 5-10](image.png) A scanning electron microscope of a papermaking fiber, illustrating the fibers as a hollow flexible rod-like particle.

### 5.3.1 Pressure filtration unit

The pressure filtration unit is designed for various measurements during out-of-plane compression, Figure 5-11. The principle is that an impermeable and movable piston with a diameter of 80 mm and a stroke length of 81 mm is compressing and thus dewatering the papermaking fiber suspension towards a dewatering plate. This plate consists of 1 mm holes with totally an open area to flow corresponding to 18%. The left-hand side of the movable piston in Figure 5-11 represents the hydraulic system being fed with pressurized oil. Two high-pressure sealing is a barrier between oil and fibers. The hydraulic system generates a constant flow rate that is varied by use of a hand valve. Hence, the piston is moved at constant speed in the trials. The load on the piston was measured by use of a hydraulic pressure sensor on the feed-side of the
piston. A pressure sensor, HAD 4745, with a measurement range up to 100 bar, is used for this purpose, which corresponds to a surface pressure of 9.4 MPa on the piston. The pressure sensor is attached directly onto the pressure filtration unit and measures the oil pressure inside the cavity. It has an accuracy in repeatability of ± 0.05% and a hysteresis of ± 0.1% relative to the full scale measurement. The position sensor is a LPC sensor with a maximum stroke length of 100 mm with a linearity of ± 0.05% and an accuracy regarding repeatability of less than 0.05%. The sensor itself was attached to the movable piston at the end of the free axis of the stroke. It was not possible to attach the position sensor in a fix position inside the PET-equipment. However, to ensure that the piston was pulled back in position so that maximum stroke length and that the position sensor was pushed together each time the equipment was installed in the PET-equipment, enabled a satisfactory accuracy when measuring the thickness of pulp suspension. The pressure filtration unit is in principle, axi-symmetric facilitating the analysis of the tomography results from the PET.

Figure 5-11. Pressure filtration cell, used in the PET experiments.

5.3.2 Positron emission tomography

Positron emission tomography (PET) is a nuclear imaging technique which produces a three-dimensional image of the studied volume. The system detects pairs of gamma rays emitted indirectly by a positron-emitting radionuclide. Each emitted positron annihilates with a nearby electron producing two collinear 511-keV gamma rays traveling in opposite directions. Simultaneous detection by positron-sensitive detectors defines a line close to which the
radioactive decay must have occurred. By detecting many of the decays in the volume the activity can be determined. The principle is that images are scanned along parallel planes with a predefined thickness and resolution. The information obtained from each individual plane is then combined in order to obtain a three-dimensional image of the volume studied. In the present case the volume is constructed from 31 parallel planes that are 8.06 mm thick, which gives a total axial length of about 250 mm. Each axial plane is made up 256 X 256 pixels. The PET-camera used to collect the gamma radiation has a resolution for each pixel of 0.96 mm in each direction. Three-dimensional images are constructed and illustrate the location of the tracers inside the volume.

As mentioned, in the present case an attempt was to display gradients in the fiber network. A fraction of the fibers was therefore doped with Flourine-18 ($^{18}\text{F}$) which has a half-time of 120 minutes and was produced at the company TRIUMF in a positron emitter. The fluorine attaches to the lignin in the fibers. The main bulk of the suspension consisted of a fully bleached and baled Scandinavian Softwood Kraft pulp named Celeste pulp. The amount of Celeste pulp was too low, hence fibers from a bleached CTMP suspension was labeled with the isotope. The suspension of doped CTMP fibers was divided in two fractions as to fiber length, obtained by use of the Bauer-McNett classifier. The classes defined will be referred to as the “long” and “short” tracer, given in Table 5-3. The aim by using different fiber lengths in the measurement was to be able to study how small particles move inside the suspension. After being radioactive labeled the fibers were mixed into the host suspension. The amount of CTMP in the suspension was calculated so that the gamma radiation should be about 2 microcuries which corresponds to 74 kBq. For each recording transmission scans were carried out in order to calculate corrections for photon attenuation. Followed by an emission scan that generated data.

<table>
<thead>
<tr>
<th>Table 5-3. The fiber length of the labeled CTMP and for the Celeste pulp.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Arithmetic average fiber length (mm)</strong></td>
</tr>
<tr>
<td>Small Fraction <strong>CTMP</strong></td>
</tr>
<tr>
<td>Large Fraction <strong>CTMP</strong></td>
</tr>
<tr>
<td><strong>Celeste pulp</strong></td>
</tr>
</tbody>
</table>
5.3.3 Set-up

The procedure for the filtration experiments is described as follows. The suspension was cautiously placed into the cavity with an initial consistency by mass aimed at 7% with a basis weight corresponding to 5 kg/m². After filling, the cavity was closed by tightening the screws. The pressure filtration cell was mounted in the PET equipment at the same position in every trial. The correct positioning was secured by use of a laser being a part of the PET-equipment. Before initiating the first transmission and emission, the suspension was compressed about 10 mm in order to certify that the entire volume inside the cavity was filled with pulp suspension. After the scan the suspension was compressed at a constant rate. The piston was manually stopped when the height of the cavity was about 16 mm, which corresponds to 13 pixels in the dewatering direction which was judged to be enough to trace any occurrences of gradients in the pulp suspension during the second and final emission scan. This procedure was repeated for a number of velocities of the piston and for the two types of mixtures presented in Table 5-3, illustrated in Table 5-4. The signals from the pressure and position transducers were logged in a DAQ/BOOK 3000.

<table>
<thead>
<tr>
<th>Emission No.</th>
<th>Material</th>
<th>Velocity, mm/s</th>
<th>Height Em initial, mm</th>
<th>Height Em after, mm</th>
<th>$\phi$ average init</th>
<th>$\phi$ average end</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Small</td>
<td>2.31</td>
<td>72.84</td>
<td>13.04</td>
<td>0.05</td>
<td>0.31</td>
</tr>
<tr>
<td>3</td>
<td>Small</td>
<td>7.13</td>
<td>71.04</td>
<td>14.04</td>
<td>0.06</td>
<td>0.29</td>
</tr>
<tr>
<td>4</td>
<td>Small</td>
<td>3.28</td>
<td>72.04</td>
<td>13.04</td>
<td>0.06</td>
<td>0.31</td>
</tr>
<tr>
<td>5</td>
<td>Small</td>
<td>3.05</td>
<td>74.04</td>
<td>14.04</td>
<td>0.05</td>
<td>0.29</td>
</tr>
<tr>
<td>6</td>
<td>Large</td>
<td>5.45</td>
<td>73.04</td>
<td>14.04</td>
<td>0.06</td>
<td>0.29</td>
</tr>
<tr>
<td>7</td>
<td>Large</td>
<td>2.00</td>
<td>74.04</td>
<td>14.04</td>
<td>0.05</td>
<td>0.29</td>
</tr>
<tr>
<td>8</td>
<td>Large</td>
<td>1.63</td>
<td>72.04</td>
<td>13.34</td>
<td>0.06</td>
<td>0.30</td>
</tr>
<tr>
<td>9</td>
<td>Large</td>
<td>8.29</td>
<td>72.04</td>
<td>14.54</td>
<td>0.06</td>
<td>0.28</td>
</tr>
<tr>
<td>10</td>
<td>Large</td>
<td>2.06</td>
<td>72.04</td>
<td>13.64</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

5.3.4 Results

The transmission scan provided the necessary calibration for calculating the true activity, consequently the data could be reconstructed into three-dimensional emission images, as illustrated in Figure 5-12. Activity was related to the mass of radioactive fibers from an independent calibration procedure, (Martinez, Buckley et al. 2001). By studying the 3D pictures of the emission scan for Emission 2, Figure 5-12 it is indicated that in the radial direction the labeled fibers are uniformly mixed into the host suspension. This is noticed in the left-hand side
In axial direction the distribution is noticed to be more narrowly distributed, especially closest to the filtration plate, which is found in the middle and to the right in the picture, Figure 5-12.

**Figure 5-12.** 3-D results from emission scan for trial 2 when the piston is stopped at 13mm. The left-hand picture is representing the compressed material from the filtration plate. The picture in the middle is representing the top view gravity pointing into the paper. On the right-hand the picture is from beside, where the gravity is acting from left to right.

It was not possible to achieve more results from the measurements than presented in Figure 5-12, since the outcome from the transmission was not as expected. The calibration was due to that not fully performed and it was not possible to produce reliable results. For instance, the overall challenge with the data was to determine the originating position of the signal. By use of the time shift between the detection of each emitted positron the originating position can be determined. However, when the positron is passing the pressure filtration cell with different amounts of material the time shift becomes too large. Hence, the originating position was due to that wrongly determined, and the results from the measurements are due to that not reliable. Hence, the labeled material noticed in the outlet pipe in Figure 5-12 is most likely wrongly placed signals, during the measurement γ-ray test was perform on the expelled fluid which indicated that it was not including any radioactively labeled particles.

To summarize: The main result from these measurements was that there is no traceable difference in concentration gradient between the experiments. This suggests that the resolution of the image was either too coarse as compared to the length scale of the concentration gradient or simply that the concentration gradients in the system were too small to be detected. It is also possible that the emissions from the doped fibers were considerably distorted by the design of the compression cell as proposed by a large lag in the signals.
6. Summary/Conclusion

The focus of this thesis was to study the flow of a Newtonian fluid through a compressible cellulose fiber network; both air and water were considered. The work was divided into a number of studies in which information was gathered regarding the ease at which water flows through the network under essentially steady-state conditions to define the permeability of the fiber networks. In these initial studies a number of novel experimental devices were developed in which the in-plane permeability as well as the out-of-plane permeability was determined in order to be able to study some cases later on in the thesis. Interesting side-results were that the fiber networks become anisotropic as to permeability as they were deformed and that the permeability of Hardwood pulps was higher overall than Softwood pulps especially at low porosities. The challenge with these types of experiments was that network may deform under loading caused by the flowing fluid. To describe the phenomenon inside the fiber suspension during loading another parameter except the permeability need to be known, that describe the compressive yield strength of the fiber networks determined as the solid fraction. The exact mechanism by which the network deforms under load remains an open question. Hence, a flow field study in a unit operation was performed. The flow field study was performed and compared with collected field data in mathematical models developed in this thesis. By scrutinizing the equations for a felt press it were noticed that the velocity of the belt and the viscosity of the penetrating gas can be altered without affecting the pressure distribution. It was moreover found that small alterations to the permeability near the nip of the press may result in huge differences in the pressure at the entrance of the press. In the validating procedure, it was shown that model parameters could be physically adjusted to obtain reasonable agreement with experimental data.

To increase the knowledge in how the wood fiber network deforms under load a pressure filtration study was performed. A uniaxial compression study by varying the pressure filtration speed was done by use of a mathematical model. In the validation procedure between the experiments and model prediction a rate dependent lag in the system was detected. The explanation of the lag effect must be found inside the material itself. Hence, the lag should be related to the solid part or to the fluid part inside the fiber network or to a combination of both, Paper A

One effect that might describe the lag is related to the fiber-fiber interactions that occur during compaction of fiber suspension. The described network consists of hollow, flexible rod-like particles that are partly or fully saturated. Due to the lumen volume of the fibers the network can be described as a bimodal, considering the differences in pore scale. When the fiber-fiber interaction consists of only a couple of contact points all pores are still communicating. However, when the fiber-fiber interaction is increased the communication between the pores decreases and the mechanics to flow is fully controlled by the small pores. This mechanics is more pronounced when the filtration rate is large. This pressure filtration process is modeled by considering that the energy required to compress the network must balance the viscous dissipation rate out from the
small pores. Closure equations were developed and tested experimentally by comparison to the pressure developed to drive the piston. Good agreement was found. The length scale for the viscous dissipation was found to be twice the fiber length.

In subsequent work an attempted to confirm the form of this relationship independently through novel visualization methods was performed, i.e. positron emission tomography. This technique gives an opportunity to get an insight in how the creation of solidity profile occurs. The filtration of a papermaking fiber was studied from a solidity of 5% up to 31%. The system detects pairs of gamma rays, if the gamma rays are collected with a small difference in time a calculation can be performed to determine the originating position of the signal, 3D pictures can be imaging. The pressure filtration cell used in the measurements disturbed the transmission scan, i.e. the calibration of the measurements was not fully performed. Hence the originating position for the signal was wrongly placed. The utility of this approach may due to that be discussed.
7. **Recommendation**

By increasing the pressure filtration rate even further, micro channels may be introduced. These micro channels are generated by a too high pressure drop through the network or by large movements of particle, illustrated in Figure 7-1, causes a drastically decrease in hydraulic pressure drop for the fluid to flow. Consequently an increased pressure is applied on the solid phase. These filtrations rate occurs especially in dewatering presses located in the pulp mills. Continuing this work and studying the shift in scales, where the homogenous material shifting into micro channels, would be a further step into gain knowledge in the topic of pressure filtration.

![Figure 7-1. Illustrate generation of channels inside the wood fiber network.](image)

Figure 7-1. Illustrate generation of channels inside the wood fiber network.
Nomenclature

- **A** Area \((m^2)\)
- **b** Kozeny constant = 5.55 \((-)\)
- **B₁, B₂ and B₃** Empirical constant dry permeability function \((-)\)
- **C₁, C₂** Empirical constant permeability function \((-)\)
- **C₀** Coarseness \((mg/m)\)
- **Cᵣ** Consistency by mass \((-)\)
- **c, n** constant in Eq. (2-4) \((-)\)
- **d** diameter \((m)\)
- **E** Youngs modulus of the fiber \((Pa)\)
- **E₁, E₂** Empirical constant compressibility function \((Pa)\)
- **E₁ and E₂** Empirical constant compressibility function \((-)\)
- **G** shape factor \((-)\)
- **h** height of the specimen \((m)\)
- **k, K** Permeability \((m)\)
- **F, \mathbf{F}** fluid velocity, vector quantity \((m/s)\)
- **ξ** pore length \((m)\)
- **L** Spatial length of belt press model \((m)\)
- **m** mass \((kg)\)
- **p** Pressure \((Pa)\)
- **R** gas constant \((-)\)
- **r₀** pore radius \((m)\)
- **r** radius \((m)\)
- **S** perimeter \((m)\)
- **S₀** Specific surface \((m^3/m^2)\)
- **t** time \((-)\)
- **T** Temperature \((-)\)
- **U, \mathbf{U}** particle velocity, vector quantity \((m/s)\)
- **v** Superficial velocity of fluid \((m/s)\)
- **V** Volume \((m^3)\)
- **vᵣ** velocity of the belt \((m/s)\)
- **w** Basis weight \((kg/m^2)\)
- **W** work on the system \((Nm)\)
- **x, y** Spatial direction \((m)\)
Greek

\( \sigma \)  
\( \lambda \)  
\( \phi = (1-\varepsilon) \)  
\( \varepsilon \)  
\( \beta \)  
\( \rho \)  
\( \mu \)

Applied pressure (Pa)
Dynamic compressibility function
Solidity (-)
Porosity (-)
Parameters of the porous media Eq. (2-1) (1/m)
Density (kg/m³)
dynamic viscosity (Pas)

Index

\( b \)  
\( c \)  
\( e \)  
\( F \)  
\( f \)  
\( fw \)  
\( g \)  
\( j \)  
\( lu \)  
\( l \)  
\( s \)  
\( t \)  
\( wa \)  
\( s \)  
\( v \)  
\( y \)

bulk
cross-sectional
effective
Pressure filtration
fiber
fiber wall
gas phase
EPS spheres
lumen
liquid
solid phase
total
fiber wall
sphere
belt
yield
References


Part II

PAPERS
A METHOD TO MEASURE THE PERMEABILITY OF
DRY FIBER MAT
A METHOD TO MEASURE THE PERMEABILITY OF DRY FIBER MATS

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ABSTRACT

Close to the finalization of the medium density fiberboard process, a fairly thick bed of loosely entangled fibers is compressed in a belt-press to often less than a tenth of its original unstressed thickness. This single unit operation is very important to consider when the manufacturing process of the boards is to be optimized. Despite this, there is a lack of knowledge of the interaction between the fiber mat strength and how the fluid flows through it, i.e. de-aeration. Thus, it is of greatest importance to find reliable methods for studying this stage of the manufacturing process. Following this quest, a method is developed with which the gas permeability of fiber mats can be measured. The method offers the potential to measure the permeability at different flow rates and thus at arbitrary pressure gradients through the material. The method is successfully validated with a porous reference material consisting of polymer spheres, and it is shown that the flow follows Darcy’s law at the flow rates of interest. Finally, the method is demonstrated by a presentation of permeability measurements on fiber mats consisting of spruce fibers.

Keywords: Medium density fiberboard, gas permeability, anisotropic permeability, experimental validation, porous flow.

INTRODUCTION

This study covers a part of the manufacturing process of medium density fiberboard, (MDF). Close to the final formation, a fairly thick mat of loosely entangled fibers is compressed in a belt-press to often less than a tenth of its original unstressed thickness. During this process, a large amount of air is forced through the porous mat generating pressure on it due to a flow resistance between the air and fibers, a procedure often termed de-aeration. The magnitude of the force is dependent on the permeability of the fiber mat, the speed of the belt, the geometry of the belt-press, and the potential for air to escape via permeable belts. If the force generated by the airflow becomes too high, the fiber mat will break. In order to mimic the flow of air and the corresponding pressure gradient, the resistance to flow must be found. One reliable method for networks with complex geometry is to measure the resistance to flow at discrete points and to fit suitable resistance models to the results. Measurements of the resistance to flow of porous materials are, however, not straightforward. To
start with, airflow through porous media does not generally follow Darcy’s law. There are at least three possible reasons for this: 1) The Reynolds number, in many cases, becomes too high and inertia effects must be considered. Inertia effect occurs when the flow regime is approaching the transition region between laminar and turbulent flow. The inertia effect is usually dealt with by using the Forchheimer Equation (Whitaker 1996) that may be written as follows:

\[
\frac{dp}{dx} = \frac{\mu}{k} v + \beta \rho_s v^2,
\]

where \( p \) is the pressure, \( v \) the superficial velocity, \( \mu \) the viscosity, \( k \) and \( \beta \) parameters of the porous media, and \( \rho_s \) the fluid density. If \( \beta \) is set equal at zero, \( k \) becomes equal to the permeability \( K \) and the Darcy’s equation is found. Hence, in order to use Eq. (1), two material parameters must be determined. 2) Besides inertia effects, if the pressure drop caused by the flow rate overcomes the fiber mat stress, the fiber mat may deform. This phenomenon has been shown to result in a linear pressure velocity relationship up to a certain pressure difference, while above this pressure the velocity remains constant as the driving pressure is increased (Belkacemi and Broadbent 1999). 3) The non-Darcian behavior can also be attributed to the molecular effect being important for gas flow at low pressures in very small pores. The effect is that measured gas permeability is higher than liquid permeability in the same porous media (Bear 1972; Scheidegger 1972). The reason for this is that the mean free path of the gas molecules approaches the dimensions of the pores. This results in a Knudsen flow, implying that there is a slip between the walls of the pores and the gas. That would result in a too high measured flow rate for a given pressure drop. For \( \text{N}_2 \) at a pressure of one atmosphere and a temperature of 300 K, the mean free path is 22 nm (Thompson 1972).

There are a substantial number of published findings on the permeability of liquids penetrating fiber networks, while only a few studies consider characteristics of the flow of gas through fiber networks. One technique often used with liquids that also applies to gases is the parallel flow saturated technique, which is very simple and has also proven to be reliable, (Lundström et al. 2000). One drawback that must be kept in mind, however, is that relatively large channels may be formed between the sealing and the fiber mat leading to too high flow rates and incorrect permeability values. Another disadvantage is that errors in permeability values are obtained if the flow is not in the main permeability directions (Lundström et al. 1998). Only a few studies are available regarding gas flow. Sullivan and Hertel (1940) estimate the permeability of glass fibers, while Bouazza and Vangpaisal (2003) focus on clays. In both cases, the measurement is carried out in a fixed control volume where the pressure drop is carefully measured at a constant flow rate. Yet another approach for determining permeability and often applied to fibrous material is to use dynamic compression equipment. A permeability model has been established for pulp at low basis weight for this type of set-up (Buntain and Bickerton 2003). One uncertainty in this kind of experiment is that the volume fraction in the suspension is not generally constant in the compression direction (Zhu et al. 1995; Lu et al. 1998).

The objective of this paper is to present an evaluation of equipment that has been developed to measure the gas permeability of a porous material consisting of wood fibers, typically a fiber mat. The equipment offers the potential to measure the permeability in two independent directions in order to classify the degree of anisotropy at different flow rates and different pressure gradients.

**Materials**

Permeability measurements were carried out on two types of material: reference material expandable polystyrene (EPS) spheres used to validate the permeability equipment, and fiber mats, which are the main constituents in the MDF material. The EPS material has the following advantages when using it as a reference material: 1) Its permeability is in the same range as the fiber network at high porosity; 2) It is stable
under testing conditions; and 3) its permeability can be estimated by analysis. To fulfill these requirements, EPS spheres with a mean diameter of 0.62 mm, delivered by the Finnish company StyroChem, were used. This polymer is made of styrene containing pentane as a blowing agent. An image analysis of the spheres was performed in order to estimate their diameter. The image analysis was conducted by examining the spheres in a microscope connected to the software “Image pro plus.” The analyzed image had a resolution of about 47 pixels per mm, depicted in Fig. 1. The categorization of single spheres was accomplished by setting a threshold value for the roundness defined as:

$$r = \frac{S_s^2}{4 \cdot \pi \cdot A_s}.$$  \hspace{1cm} (2)

Here $S_s$ describes the perimeter and $A_s$ denotes the cross-sectional area of the spheres, respectively. Hence, for a perfect spherical particle, the roundness value is 1.0. The area in Fig. 1 that deviates from spherical shape was excluded in the analysis of the diameter of the spheres by setting the roundness value at 1.1. By varying the roundness value from 1.1 to 1.5, the mean diameter changed by only 0.8%. Several methods were tested to determine the porosity of the EPS spheres under dry conditions. The porosity of a material is defined as the fraction of the bulk volume of the porous sample that is occupied by pore or void space. The methods used when estimating the porosity of the EPS material were based on the density method, which yields the total porosity. The density method depends on the ratio between the bulk density of the sample and the density of the solid particles. The density of the EPS spheres, $\rho_s$, was obtained from the supplier, 1010 kg/m$^3$; the bulk density, $\rho_c$, was determined by measuring the mass of the spheres used in the measurement, (cf. Fig. 2). The total porosity is expressed as:

$$\varepsilon_s = 1 - \frac{\rho_c}{\rho_s}.$$  \hspace{1cm} (3)

Spruce chips from Östrand, Sweden, were degenerated in a burnisher equipment at the Technology Center in Sundsvall, Sweden. The outcome from the equipment is fibers. Of importance, the fibers are relatively long and strongly
crimped, thus enabling entanglement to neighboring fibers as illustrated in Fig. 3. In order to determine the geometrical parameters of the fibers forming the networks, an image processing was performed by using Pulp Quality Monitor (PQM)™ equipment. This system gives the fiber diameter as an arithmetic mean value, while the fiber length is specified as a weighted average length. The coarseness value is calculated from the total measured fiber length and the mass of the fiber sample. The resolution of the image obtained was about 15 μm per pixel. The morphological data of the measured spruce fibers are depicted in Table 1. The results from the refining illustrate that the outer mean diameter of the fibers is in the same range, except for the fibers that were degenerated one year later.

As for the bed of spheres, it is important to determine the porosity of the fiber mat. This is not straightforward since the fibers themselves are porous, (cf. Fig. 4), i.e. a wood chip consists of many hollow fibers. Hence, a number of correlation parameters have been presented for pulp suspension; one important parameter is the total porosity described by Wikström and Rasmuson 1998 and Vomhoff and Norman 2001. The total porosity is defined as the total volume of voids, i.e. both lumen volume and the free pore space outside the fibers in relation to the total control volume, illustrated by Wikström and Rasmuson (1998), compare Fig. 5, which may be expressed as:

\[ e_t = 1 - \frac{V_f}{V_f + V_{lu} + V_g} \]  

(4)

where \( e_t \) describes the total porosity for the fiber mat, the fiber wall volume \( V_f \), the free volume between the fibers \( V_g \), and the lumen volume inside the fibers \( V_{lu} \). The total porosity for the fiber mats can also be expressed in terms of the

<table>
<thead>
<tr>
<th>Batch no.</th>
<th>Average outer diameter [μm]</th>
<th>Average fiber length [mm]</th>
<th>Coarseness value [mg/m]</th>
<th>Dryness [kg/kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>29.0</td>
<td>1.80</td>
<td>0.50</td>
<td>0.93</td>
</tr>
<tr>
<td>2</td>
<td>29.3</td>
<td>1.84</td>
<td>0.43</td>
<td>0.93</td>
</tr>
<tr>
<td>3</td>
<td>28.5</td>
<td>1.85</td>
<td>0.37</td>
<td>0.93</td>
</tr>
<tr>
<td>4</td>
<td>32.18</td>
<td>2.14</td>
<td>0.64</td>
<td>0.91</td>
</tr>
</tbody>
</table>

**Table 1.** The morphological data of the spruce fiber mats and the dryness value of the material at the time of the measurements. Batch 4 denotes the measurement conducted more than one year later compared to the other ones.
density method suggested by (Vomhoff and Norman 2001) as:

\[ \varepsilon_r = 1 - \frac{w}{h \cdot \rho_f}, \]  

(5)

where \( w \) is the basis weight, \( h \) the thickness of the sample, and \( \rho_f \) the fiber wall density.

**MEASURING UNIT**

To experimentally derive the permeability of the fiber mats, a permeability measurement unit has been developed which is designed for measurements of in-plane permeability as well as out-of-plane permeability, (Fig. 2). If the latter direction coincides with one principal direction, the full 3D-permeability tensor can be derived. To determine the permeability for the porous material, Darcy’s law is used:

\[ \frac{\partial p}{\partial x} = -\frac{\mu}{k} v, \]  

(6)

where \( v \) is the superficial velocity, \( \mu \) is the dynamic viscosity of the fluid, \( K \) represents the intrinsic permeability, and the gradient on the left-hand side is the pressure drop of the fluid. Since air is a compressible fluid, it is necessary to rewrite Darcy’s law by use of the equation of state:

\[ pvA_e = \dot{m}RT, \]  

(7)

where \( R \) is the gas constant, \( T \) is the temperature of the gas, \( p \) is the fluid pressure, \( A_e \) is the cross-sectional area of the cavity, and \( \dot{m} \) the mass flow. By integrating the combination of Darcy’s law (Eq. 6) and the equation of state for air (Eq. 7) in the flow direction and by assuming a homogenous porosity profile, the gas permeability is expressed as:

\[ K = \frac{2\mu nRT h}{A_e(p_1^2 - p_2^2)}. \]  

(8)

To derive the out-of-plane permeability, air is forced through a perforated plate placed at the base of the measuring cell and into the fiber network by the means of an applied pressure gradient, (cf. Fig. 2). The air is allowed to leave the cell through a perforated top wall. Maximum volume of the cavity is 0.19 m × 0.311 m × 0.4 m where the last dimension denotes the height. In the current set-up, flowmeters (4 to 25 m³/h, or 30 to 390 m³/h) were connected externally with the permeability equipment at the outlet by a tube with an accuracy of ±0.5% of the calibrated span. In addition, a pressure transducer ranging from 0 to 16 kPa was placed close to the flow gauges in order to determine the mass flow. Pressure transducers (0 to 20 kPa, or 0 to 200 kPa) were also connected to the permeability equipment at the inlet position, marked as \( p_1 \) in Fig. 2; the sensitive one was used when possible in order to reduce experimental error. The pressure transducer placed at the outlet had a range of 0 to 7.5 kPa, marked as \( p_2 \) in Fig. 2. The measurement error of the pressure transducers was ±0.2% of the calibrated span. The height was measured by a linear magnetic position sensor with a measuring length of 1.0 m. The maximum deviation of the magnetic position sensor was ± 0.05% of the calibrated span. The permeability measurements were conducted under stationary conditions in the sense that a constant flow rate was applied through the fiber mat while the height of the cavity was held constant. Since the permeability of the fiber mat is strongly dependent on the porosity, additional measurements were performed by lowering the upper plate. This procedure was repeated until the lowest possible volume of the cavity was reached, with respect to the limit of the pressure transducer, or until the maximum load from the compression was achieved.

For the measurement of the in-plane permeability, the solid walls were replaced with perforated plates, and rubber cloths were placed on the top and bottom surfaces to prevent air from leaving the cavity in the out-of-plane direction. Air was forced through the sample from the left chamber to the corresponding right one, cf. (Fig. 2) where the positions of the pressure transducers can be spotted.

The systems presented have several sources of error such as:
Pressure losses through the sealing between the piston and solid walls,
edge effects in the fiber mat closest to the solid wall,
pressure, flow rate, and position transducers,
non-uniform flow rate due to compression of air,
temperature variations inside the cavity due to variation in temperature of the flowing gas.

Some of the sources are more difficult to estimate than others, but by studying their effects on the permeability in Eq. (8), it is possible to distinguish the most sensitive ones. By scrutinizing the parameters, it is obvious that the inlet and outlet pressure must be measured very accurately. In addition to this, a pressure loss test without fibers in the cavity was performed in order to study how the flow resistance through the perforated walls influenced the permeability. It was shown that the pressure drop through the walls was negligible.

A final remark on the performance of the measurement is that a fiber bed with no constraints would compress homogeneously. A hypothesis is that with constraints, for instance due to friction at the side walls, an inhomogeneous material may be obtained, the estimation of the permeability due to that effect will be misleading. Hence, during the permeability measurements, the applied force on the fiber bed was logged showing that the reaction force from the bed towards the piston decreased during the measurement, i.e. the fibers were redistributed. The permeability measurement was not established until force equilibrium was reached.

RESULTS AND DISCUSSION

Validation of permeability equipment

Measurements carried out in the out-of-plane set-up show that the apparent permeability of the EPS spheres is dependent on the Reynolds number defined as:

$$\text{Re} = \frac{\text{v} \cdot d \cdot \rho \cdot g}{\mu},$$

where v is the superficial velocity, i.e. flow rate divided by the cross-sectional area of the cavity, d is a characteristic length scale, which for the spheres was set at the average mean diameter, (cf. Fig. 6). At high Reynolds number, the reduction in apparent permeability is in accordance with the classic results obtained by Rumpf and Gupte (1971), who attribute these phenomena to inertial effects, (cf. Eq. 1). At low Reynolds number, the strong non-Darcian behavior can either be due to the Knudsen effect discussed in the introduction or may just be a result of erroneous values obtained from the measurement sensors. The latter is a result of low flow rates and a correspondingly low pressure drop that was generated. One consequence of a Knudsen flow is that the quantity of gas flowing through a capillary is larger than would be expected from the Poiseuille’s formula at low pressure-driven flows. This occurs in cases where the distance between the walls inside the porous material is in the same magnitude as the free molecular path length of the flowing fluid. The Darcy’s law applies for Reynolds numbers approximately between 3 and 12, (cf. Dullien 1992). By performing measurements in this range, it was possible to validate the permeability equipment.

![Fig. 6. Non-dimensional apparent permeability of the EPS material. Triangles illustrate the permeability measurements conducted at too low Reynolds numbers. The valid range of applicability of Darcy’s law is marked as circles. The diamonds denote a too high flow rate where the inertia effects occur, cf (Dullien 1992).](image-url)
range, the equipment can be validated by comparing results to theoretically derived expressions for permeability. One such expression that has been successfully validated with experiments is the one derived by Rumpf and Gupte (1971):

\[ K = \frac{d^2 \cdot e_s^{5.5}}{5.6 \cdot S} \]  

where \( d \) is the diameter of the spheres, \( e_s \) is the porosity of the spheres, and \( S \) is a shape factor equal to one for a narrow distribution of diameters and equal to 1.05 for wider ones. Setting \( S \) at 1.0, being the most appropriate presumption for the bed of spheres, yields a fit to the measured permeability, (cf. Fig. 7).

Permeability of fiber mats

In order to evaluate the equipment for fiber mats, the permeability was measured as a function of time and Reynolds number. Regarding the function of time, the permeability was practically the same when the measurements were carried out with more than one year’s interval on two different batches. The batches were formed and degenerated at the specific day when the measurements were conducted, (cf. Fig. 8 and Table 1). This indicates that the permeability equipment is stable, and the procedure of forming the fiber mat has been similarly performed, i.e. the systematical errors have the same influence on the permeability measurements on the different fiber mats. A direct comparison between the permeability measurements gives a maximum deviation of less than 8%. Unlike the permeability measurement on spheres, the permeability on fiber mats was unaffected by the Reynolds number in the measured flow interval, (Fig. 9), i.e. Darcy’s law is due to that valid. The Reynolds number for the gas flowing through the fiber mat was defined in a similar procedure as for the EPS material, (cf. Eq. 9). The characteristic length scale was set at the average fiber diameter obtained from the PQM measurement.

Results of the measured permeability for the fiber mat in the in-plane and in the out-of-plane direction are given in Fig. 10. It is shown that the permeability of the spruce fiber mats has an anisotropic behavior at low porosity as outlined by Håkanson et al. (2005) for similar material. In
In order to find the level of anisotropy, the measured permeability was fitted to the following empirical equation, similar to the equation found by Koponen (1998) for pulp suspensions:

$$k = D^2 \cdot \frac{C_1}{(e^{C_2 (1-e^{C_3})} - 1)^{C_4}}$$

where $C_1$, $C_2$, and $C_3$ are empirical constants for the wood fiber mats, and $D$ is the diameter of the fiber. The percentage difference between the in-plane and out-of-plane permeability is illustrated in the right-hand axis in Fig. 10. The measurement at high porosity should give the same permeability since the fiber mat is formed in a procedure where the fibers are more or less randomized. Even though the forming of the fiber mat was performed in a similar procedure, an oriented fiber mat could have occurred, since the first permeability value was determined at a lower porosity level than the actual forming one. At lower porosity, the difference between the in-plane and out-of-plane direction is around 40%. A re-arranged fiber mat from a random to an oriented structure could explain the differences in the results. If so, the differences should go towards an asymptotic relationship since the permeability is solely dependent on the geometry of the material (Scheidegger 1972). The geometrical dependency of the permeability is related to the square of a typical length scale such as the particle diameter. If the material is rearranged from a randomized to an orientated fiber mat structure, the typical length scale in the flow direction would change. Consequently, the ratio of the permeability in out-of-plane and in-plane direction would go towards an asymptotic value.

**CONCLUSIONS**

A method has been developed with which the gas permeability of fiber mats can be measured. The equipment was successfully validated with a porous bed consisting of polymer spheres following the results given by Rumpf and Gupte (1971). With the spheres, it was shown that the flow follows Darcy’s law in an intermediate range of Reynolds numbers approximately between 3 and 12. At higher Reynolds numbers, the apparent permeability decreased, which can be related to inertia effects. At lower Reynolds numbers, the increased permeability can be explained by the Knudsen effect, as pointed out by Bear (1972) and Scheidegger (1972) or by experimental errors.

None of these phenomena were observed in
the fiber mat measurements. Regardless of the fiber volume fraction, the permeability was not influenced by Reynolds number at the condition tested. The level of the measured fiber mat permeability was about three levels of magnitude lower to two times higher than the measured permeability of the bed of spheres.

As final quality control of the method, the permeability of fiber mat produced in the same burnisher equipment was measured but separated by an interval of more than one year. The permeability of these fiber mats had practically the same permeability versus porosity relationship. This finding really ensures us that the method has been valid for all experimental series.

The permeability experiments for the in-plane and out-of-plane direction indicated that the distribution of fibers at high porosity is oriented more or less randomly. A hypothesis is that the compression of the fiber mat forces the fibers to re-arrange from a random to an oriented structure. The structural changes inside the fiber mat result in a network with an anisotropic behavior, which seems to be the case in the low porosity region. Such behavior is outlined elsewhere (Håkanson et al. 2005) for a similar material.

In summary, the method developed is reliable and seems to produce results with high quality. This encouraged us to expand the experimental study and deepen the analysis in order to present a model of the de-aeration of the belt-press in a forthcoming paper.

NOMENCLATURE

- $A$ = The cross-sectional area [m$^2$]
- $C_1, C_2, C_3$ = Empirical constants for the permeability model valid for fiber mats
- $D$ = Fiber diameter [m]
- $d$ = Sphere diameter [m]
- $F$ = Applied force [N]
- $h$ = Sample thickness [m]
- $K$ = Intrinsic permeability [m$^2$]
- $k$ = Parameter in Forchheimers formulation [m$^2$]

Fig. 10. Non-dimensional plot of measured permeability on spruce fiber mats. Data points are from measurement performed in in-plane and out-of-plane direction. The permeability model described in Eq. (11) has been used to determine the percentage difference between the out-of-plane and in-plane differences. The empirical constants are given in Table 2.
\( \dot{m} = \) Mass flow of the fluid [kg/s]
\( p = \) Air pressure [Pa]
\( R = \) Gas constant (air as an ideal gas) \( R = 287 \text{ at } T = 300 \text{ K} \) [J/kg K]
\( \tau = \) Roundness value of the spheres
\( S = \) Shape factor
\( T = \) Temperature of the gas [K]
\( V = \) Volume [m³]
\( w = \) Basis weight of fiber sample [kg/m²]
\( x = \) Measurement direction in the permeability equipment [m]

Greek
\( \beta = \) Parameter in Forchheimer’s formulation [1/m]
\( \varepsilon = \) Total porosity of the measured material
\( \mu = \) Dynamic viscosity [Pas]
\( \rho = \) Density of the specific material [kg/m³]
\( \rho_{\text{pu}} = \) Bulk density of fiber mat [kg/m³]
\( \rho_{\text{s}} = \) Bulk density of spheres [kg/m³]
\( \nu = \) Superficial fluid velocity [m/s]

Index
\( c = \) cavity
\( f = \) solid, i.e. fiber wall
\( g = \) air
\( l = \) lumen
\( s = \) spheres
\( t = \) fiber mat

REFERENCES


MODELING OF THE PRESSURE DISTRIBUTION IN A BELT PRESS DURING MANUFACTURING OF FIBERBOARDS
MODELING PRESSURE DISTRIBUTION IN A BELT PRESS DURING MANUFACTURE OF FIBERBOARDS

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ABSTRACT

When forming fiberboards, a large amount of air is evacuated from the dry fiber mat and the fibers are subjected to forces generated by the flow. If the forces become too strong, the fiber mat bursts and the process stops with financial loss as a result. A simplified model for the pressure field during the pressing has been derived, by starting from first principles. This model indicates that the velocity of the belt can be increased as long as the length of the press is increased, or the viscosity of the penetrating fluid is decreased in a prescribed manner. The model furthermore suggests that the pressure distribution will be unaffected by variations in the basis weight of the fiber mat as long as the basis weight is matched with an equal change in the density of the fibers. Furthermore, by numerically deriving the pressure field as a function of boundary conditions, it is shown that minor variations in the pressure at the nip may result in huge differences in the pressure at the entrance of the press. In a validating procedure, it is shown that model parameters can be adjusted in a physically reasonable way to obtain acceptable agreement with experimental data, but also that the model must be considerably improved in order to obtain quantitative conformity.

Keywords: Modeling, fiberboard manufacturing, pressure distribution, belt press.

INTRODUCTION

In the beginning of the final phase of manufacturing dry-formed fiberboards, a fairly thick mat of loosely entangled fibers is compressed to often less than a tenth of its original thickness in a continuous belt press. Consequently, a large amount of air must be evacuated from the mat, and the fibers are subjected to a force generated by the air flow. This force is in most cases balanced by the entanglement of the fibers and the friction between fibers and belts. However, it is well known in the paper board industry that if the speed of the fiber mat through the belt becomes too high the fiber network will burst and the process will be stopped. This problem needs to be overcome since increasing the speed through the belt implies a higher overall efficiency in the process. By starting from first principles we will, therefore, derive models for the pressure field during this first stage of formation.

Flow through a deformable porous media, as
the one described above, exists in several areas of application including ground water flows, reservoir engineering, oil recovery, paper-making, and composites manufacturing. A flow field is often very complex to describe, but in some cases rather simple relationships can be used. When one of two phases is a viscous and incompressible Newtonian fluid and the other is a stationary solid, Darcy’s law applies. This classic law states that the rate of fluid flow is proportional to the pressure gradient in the fluid, and holds true for low Reynolds number flow, typically less than 1–10. When increasing the Reynolds number above 10, inertia becomes important and an additional non-linear term must be added to Darcy’s law; cf. (Ergun 1952). The constant of proportionality in Darcy’s law involves the viscosity of the fluid and the permeability, which are properties of the porous medium. The permeability is thus a measure of how easily a Newtonian fluid will flow through the porous material (Bear 1972). As stated above, air flow through a porous media does not generally follow Darcy’s law. A recent study, Pettersson (2006), shows however, that the law works very well for flow through fiberboard mats as long as the Reynolds number is less than about 2, and can therefore be applied to pressing in a belt press.

Studies on the flow field in a belt press have (to the authors’ knowledge) only been published in a few cases, and then often with a focus on the later stages of the process including extensive heat transfer (Thoemen 2006; Pereira 2006). However, the process has some similarities to the flow that takes place in a press nip during dewatering of paper (Wahlström 1960; Asklöf et al. 1964; Kershaw 1972). A brief review of early models derived in this area tells us that two main methodologies have been applied that consider the in-plane flow in the felt and the transversing flow through the paper sheet, respectively (El-Hosseiny 1991).

The felt models presented in this context are invariably based on Darcy’s law, and several are one-dimensional. In more contemporary studies, such models have been developed to deal with two-dimensional multiphase flow (Kataja et al. 1992; Zahrai et al. 1997). The derived equation then becomes too complex to allow for straight analysis, and numerical methods must be applied to solve for physical parameters. High pressure gradients in the fluid may furthermore result in densification of the fiber mat, (Zhu et al. 1995; Lobosco et al. 2005). Such densifications will, however, most likely appear in flow transverse to the fiber mat where fluid induced pressure gradients are solely balanced by the stiffness of the fiber mat. For in-plane flow, movements of the fiber mat are hindered by friction forces towards the carrying belt, felt, or wire, which considerably reduce the risk for densification.

Forming fiberboards involves the flow of a gas through a deformable porous medium. This suggests that advanced numerical methods should be used in combination with experimental data to solve the flow field. Quality and trust in simulations and high-class experiments are in most cases founded on a basic knowledge of the flow. We will therefore derive analytical and semi-analytical expressions for two-dimensional flows through the belt press. The technique is similar to that used to obtain the felt models described above but the geometry, the fluid, and the boundary conditions differ. Pressure measurements from a full-scale experiment are then presented and results are compared to theoretically derived ones.

**THEORY**

The analytical and semi-analytical models will be based on the following assumptions:

- the belt press can be mimicked by the geometry described in Fig. 1;
- the flow of air follows Darcy’s law;
- the angle α is small and the flow through the side, top, and bottom walls can be neglected; and the flow is approximated to be in one direction only while keeping continuity, lubrication approximation;
- the speed of the air and the fiber bed are equal when $x = L$;
the fiber volume fraction is only a function of \( x \);
the volume and density of the fibers and the resin are constant;
the temperature is constant and no gas is generated within the press.

For the pure analytical model, it is furthermore assumed that the air is incompressible. The one-dimensional form of Darcy’s law for the relative flow between the fiber bed and the fluid can be applied according to:

\[
\frac{\partial p}{\partial x} = -\frac{\mu}{K} U = -\frac{\mu Q}{K A},
\]

(1)

where \( U \) is the relative superficial velocity between the air and the fiber mat, \( \mu \) the dynamic viscosity of the fluid, \( K \) the permeability of the fiber mat, \( Q \) the relative flow rate, and \( A \) the total area perpendicular to the flow. The gradient on the left-hand side is the pressure gradient that is to be derived. The area, \( A \), is simply given by:

\[
A = hb = \left( h_1 - \frac{(h_1 - h_2) x}{L} \right) b,
\]

(2)

where \( b \) is the width of the belt, and the rest of the parameters are defined in Fig. 1. For an incompressible fluid, the relative flow rate is directly obtained from the reduction in volume experienced by the fiber mat. Then, by applying the assumed boundary condition at the minimum height \( h_2 \), the flow rate may be expressed in terms of geometrical parameters, and the horizontal velocity component of the belt \( V \), as:

\[
Q = -Q_{\text{max}} \frac{(L - x)}{L} = (h_1 - h_2) b V \left( \frac{x}{L} - 1 \right).
\]

(3)

The pressure gradient is now simply obtained by combining, Eqs. (1), (2), and (3) to yield the following relationship:

\[
\frac{\partial p}{\partial x} = -\frac{\mu V}{K} \left( \frac{1 - \frac{h_2}{h_1}}{L} \right) \left( \frac{x}{L} - 1 \right).
\]

(4)

Assuming the above, the pressure gradient in every position \( x \) is a direct function of the velocity \( V \). It now remains to choose a model for the permeability of the fiber mat, \( K \). The most frequently used model is the Cozeny-Karman equation. This equation does not have proper micromechanical basis, but it can portray \( K \) for a number of materials as a function of the fiber volume fraction \( f \), fiber radius \( R \), and a non-dimensional shape constant \( k \) in the following way:

\[
K = \left( \frac{1 - f}{f^2} \right) k R^2 = \left( \frac{1 - f}{f^2} \right) C.
\]

(5)

The constant \( C \), having dimension \([m^2]\), is introduced for the purpose of simplifying discussion. The fiber volume fraction may in turn be expressed in terms of the basis weight, \( w \), the density of the fibers, \( \rho_f \), and the height of the press, \( h \) according to:

\[
f = \frac{w}{\rho_f h}.
\]

(6)

As previously stated, these equations are valid for incompressible fluids. Let us now instead assume that the fluid follows the perfect gas law under isothermal conditions. The density of the gas then becomes a direct function of the local pressure. By following a small volume of the fiber mat as it moves through the press, and defining the mass flow over its boundaries, the subsequent equation results:

\[
\frac{V(h_1 - h_2)}{L} p = \frac{\partial (shpu)}{\partial x},
\]

(7)

where \( u \) is the relative homogenized velocity between air and fibers. Considering the continu-
ity, it is easy to see that \( \dot{e} u = U \), cf. Eq. (1). By using this expression and Eq. (1), Eq. (7) now reads:

\[
\frac{V(h_1 - h_2)}{L} p = \frac{\partial}{\partial x} \left( \frac{K h}{\mu} p \frac{\partial p}{\partial x} \right)
\]

or by rearranging the terms:

\[
-2\mu V \frac{h_1 - h_2}{L} = \frac{1}{p} \frac{\partial}{\partial x} \left( \frac{K h \frac{\partial p^2}{\partial x}}{p} \right). \tag{8}
\]

The term on the left-hand side is independent of \( x \) while the one on the right-hand side is non-linear, since all parameters involved are functions of \( x \). There is no obvious analytical solution to this apparently neat expression, and the equation must be solved using numerical methods. It is, however, possible to express Eq. (9) in terms of more practical parameters by using Eqs. (5) and (6) in the following way

\[
-2\mu V \frac{h_1 - h_2}{L} = \frac{1}{\rho_l} \frac{1}{h_1} \frac{\partial}{\partial x} \left( \frac{h_2 - h_1}{h_1} \left( \frac{h_2}{w} - 1 \right)^3 \frac{\partial p^2}{\partial x} \right). \tag{10}
\]

It can now be seen that iterations to the parameters in the ratios on the left-hand side only affect the result if each ratio, except \( h_1 \), is changed. This height sets the scale of the problem and appears as well as a sole term in the right-hand side of the equation. Hence, according to Eq. (10), the pressure field within the press will be unaffected as long as the following equalities are satisfied:

\[
\left( 1 - \frac{h_2}{h_1} \right) \left[ \frac{\mu V}{C L} \right]^T = \left( 1 - \frac{h_2}{h_1} \right)^T \left[ \frac{\mu V}{C L} \right]^T \tag{11a}
\]

and

\[
\begin{bmatrix} \rho_l \cr w \end{bmatrix}^T = \begin{bmatrix} \rho_l \cr w \end{bmatrix}^T, \tag{11b}
\]

where the superscripts \( I \) and \( T \) denote the initial and tailored cases, respectively. Consequently, it is possible to increase the velocity of the belts as long as the length of the press is increased, or viscosity of the penetrating fluid is decreased correspondingly. Furthermore, the basis weight of the fiber mat can be changed as long as it is matched with an equal change in the density of the fibers.

### NUMERICS

In order to verify the numerical procedure, simulations were performed for a reference case where the reference material listed was processed under up-to-date conditions; see Table 1. The simulations were carried out by using the subroutine \texttt{bvp4c} in Matlab 7.0.1. This subroutine is specially designed for boundary value problems, and uses collocation with an accuracy of the fourth order, (Kincaid and Cheney 2002). An initial mesh size was set, and 100 to 400 points were tested giving the same results. Consequently, an initial mesh of 200 points was selected and used in all simulations, but the subroutine continuously adapts the mesh to the solution and additional points were added during the numerical calculation. An additional verification process including two simulations was performed. By using the results of the outlet pressure in the first simulation, for which the inlet pressure had been set, a backward calculating of the inlet pressure could be performed. The outcome of the second simulation returned the inlet pressure value that was used in the first simulation. This shows that the numerical procedure used is stable.

It is interesting to study how variations in the pressure on the inlet and outlet influence results. Not surprisingly, the spatial pressure distribution

<p>| Table 1. Parameters for the reference case. |</p>
<table>
<thead>
<tr>
<th>Geometry and conditions</th>
<th>Material parameters</th>
</tr>
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<td>( h_1 )</td>
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<tr>
<td>( h_2 )</td>
<td>0.055 m</td>
</tr>
<tr>
<td>( L )</td>
<td>7.54 m</td>
</tr>
<tr>
<td>( V )</td>
<td>0.5 m/s</td>
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</tbody>
</table>
is generally strongly dependent on inlet pressure (see Fig. 2). However, for low inlet pressures, the simulated results approach each other as the fibers move into the wedge, thus implying that the maximum pressure at the outlet has only a weak influence on the inlet pressure. Following this observation, and instead of specifying the pressures at the outlet, it can be shown that minor variations in the outlet pressure may give devastating variations to the pressure near the inlet (Fig. 3). In reality, such behavior implies that small variations in the permeability of the fiber mat may give a noteworthy pulsating flow at the entrance of the belt. The pressure gradient, in turn, responded dramatically to variations in inlet pressure for relatively low pressures until its maximum was reached. For high pressures, and close to the end of the model, the pressure gradient became independent of the inlet boundary condition (Fig. 4). In fact, the solution approached the one obtained for incompressible fluid. This verifies the numerical procedure and is yet another indication that the numerical model used is stable (Fig. 5). It now remains to weight the model against experiments to scrutinize the physical approximations made.

**EXPERIMENTAL**

The spatial pressure distribution in a poplar fiber mat with an initial moisture content of 10%
moving through a full-scale belt press has been measured with a press monitoring system called PressMan Contipro. This is a data acquisition system for in-situ monitoring of press variables, and consists of a logger and a probe. The logger can store up to 1022 data readings, and the logging frequency can arbitrarily be chosen in the interval 0.1–10 Hz. A higher spatial resolution consequently is obtained by selecting a higher frequency.

The dimensions of the logger used were:
width 48 mm, length 385 mm, and thickness 9.5 mm, (see Fig. 6). In this case, a specially designed probe of length 850 mm was attached to the logger for contemporaneous measurements of gas pressure and temperature inside the mat during pressing. The geometry of the press model was generally similar to the geometry of the press used to derive Eq. (9) but differed in detailed geometry; cf. Figs. 1 and 7. The procedure for each measurement was that at the entrance of the press, the probe was put into the fiber mat from one of its sides, thus positioning the probe tip close to the center of the mat in terms of width and the horizontal direction. The logger was then attached to the probe, and the whole system was allowed to follow the fiber mat through the entire press. After removing the system at the outfeed of the press, the data in the logger was copied to a PC. By analyzing these data, it could be concluded that the pressure increased nearly linearly up to frame 2 after which its dependency accelerated; cf. Fig. 7 and 8. It can be mentioned that repeated measurements gave similar results.

VALIDATION

To be able to compare experimental results with simulated ones, it is necessary to know the permeability of the fiber bed moving through the press. This permeability can be obtained as a function of fiber mat density by using the system presented and validated in Pettersson et al. (2006). In order to derive the constant \( C \), from such measurements, the relation between packing density and the fiber wall density of the hollow and encapsulated fibers must, however, be known. Since wood fibers are porous, as shown in Fig. 9, their bulk density can increase as the fiber mat is compressed. Let us therefore determine \( C \) for different values of the fiber density 800–1400 kg/m\(^3\) located between the bulk density of an undeformed fiber of about 450 kg/m\(^3\) and a fiber wall density of 1550 kg/m\(^3\), (Fig. 10 and Table 2). By using the processing variables in Table 3, the pressure distribution can be de-
rived with Eq. (9) as long as the pressure at the inlet or at the outlet is known. There is no obvious candidate, so let us set atmospheric pressure 0.1 MPa at the inlet of the model. By doing this, the validation shows that the slim model proposed captures the central characteristics of the pressure inside the fiber network, but that it gives considerably higher values than what were obtained from experiments, regardless of the density of the fibers (Fig. 8). There are three major reasons for this. The first explanation is simply that, in reality, air can escape through the vertical sides of the press. Second, the belts have a higher temperature than the fiber mat. From 80°C at the entrance, the temperature increases as the belts enter the heating plate section, and reaches about 150°C at frame 3 (Fig. 7). Since there is a flow of air through the bed, it is likely that the heat is continuously transported into the fiber bed affecting the glue material, lignin, which has a softening temperature of about 80–120°C. This may result in a gradient in compliance with the fiber mat and possibly a larger densification in the areas closest to the belts. If this is true, the permeability will be considerably higher in the core of the fiber mat resulting in an overall higher relative flow also in the main flow direction (Bear 1972). Third, it is likely that $\rho_f$ will increase with $f$. The open spaces between the fibers will therefore not be condensed as fast as predicted for solid fibers. This may result in a lower reduction in permeability than what is obtained from the curve fit to the measured data.

### Table 2. Results from the curve fitting to the permeability measurements.

<table>
<thead>
<tr>
<th>$\rho_f$ (kg/m$^3$)</th>
<th>$C \times 10^{12}$ [m$^4$]</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>800</td>
<td>3.78</td>
<td>0.98</td>
</tr>
<tr>
<td>1000</td>
<td>1.78</td>
<td>0.95</td>
</tr>
<tr>
<td>1200</td>
<td>1.03</td>
<td>0.92</td>
</tr>
<tr>
<td>1400</td>
<td>0.67</td>
<td>0.90</td>
</tr>
</tbody>
</table>

### Table 3. Parameters for validation.

<table>
<thead>
<tr>
<th>Geometry</th>
<th>Material parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h_1$</td>
<td>0.09 m</td>
</tr>
<tr>
<td>$h_2$</td>
<td>0.0192 m</td>
</tr>
<tr>
<td>$\rho_f$</td>
<td>800−1400 kg/m$^3$</td>
</tr>
<tr>
<td>$L$</td>
<td>3.09 m</td>
</tr>
<tr>
<td>$C$</td>
<td>7.4E-13 m$^2$</td>
</tr>
<tr>
<td>$V$</td>
<td>0.125 m/s</td>
</tr>
<tr>
<td>$\mu$</td>
<td>1.8E-8 Pas</td>
</tr>
</tbody>
</table>

---

Fig. 8. Validation as a function of position in press and density of the fibers.

Fig. 9. Schematic picture displaying fiber geometry of the internal structure of pinewood chip in cross-section. Published with permission from Staffan Palovaara, SCA Research.

Fig. 10. The discrete points are experimental data on permeability as a function of fiber volume fraction and density of the fibers. The curves are the corresponding fittings to Eq (5).
which was done for rather modest fiber volume fractions. The last two reasons imply that the permeability is generally higher than that obtained from the permeability measurements. Consequently, it is reasonable to set higher values for $C$ than that obtained from the permeability measurements. This is demonstrated by increasing the value of this parameter by five and ten times for $\rho_f = 1000 \text{ kg/m}^3$. The modeled pressure then approaches the experimentally derived ones (Fig. 11).

**CONCLUSIONS**

A model for the flow through the first stage of a fiberboard belt press has been derived. By scrutinizing the derived equations, it was shown that geometrical parameters, the velocity of the belt, and the viscosity of the penetrating gas can be altered without affecting the pressure distribution; Eqs. (10–11). The pressure was also unaffected by variations to the basis weight of the fiber network as long as it was matched with a change in the density of the fibers. By deriving the pressure field as a function of boundary conditions, it has been shown that minor variations in the pressure at the nip may result in huge differences in the pressure at the entrance of the press, which may give a pulsating flow at the end. In a validating procedure, it was shown that model parameters could be adjusted in a physically reasonable style to obtain reasonable agreement with experimental data.

Modeling of the full 3D-flow, adding the temperature field, and better describing the density of the fibers would sharpen our predictions, and is a matter for further research.

**ACKNOWLEDGMENTS**

The authors gratefully acknowledge the Swedish Research Council for its financial support.

**NOMENCLATURE**

\begin{itemize}
  \item $p$ = Air pressure [Pa]
  \item $U$ = Superficial fluid velocity [m/s]
  \item $u$ = True fluid velocity inside the fiber mat, $U^*\Re$, [m/s]
  \item $R$ = Radius of the fiber [m]
  \item $\rho$ = Density of the fluid [kg/m$^3$]
  \item $K$ = Permeability [m$^2$]
  \item $\mu$ = Dynamic viscosity [Pas]
  \item $\alpha$ = Angle between the top and bottom wall in the press [rad]
  \item $x$ = Distance in machine direction counted from the entrance [m]
  \item $L$ = Length of the model, [m]
  \item $Q$ = Flow rate of air, [m$^3$]
  \item $A$ = Cross sectional area of the fiber mat, [m$^2$]
  \item $h$ = Height of the fiber mat, [m]
  \item $b$ = Width of the press, [m]
  \item $V$ = Horizontal velocity of the belt press, [m/s]
  \item $R$ = Radius of the fibers, [m]
  \item $k$ = A non-dimensional shape constant
  \item $C$ = Constant in the Cozeny-Karman equation, a product of $k*R$, [m$^2$]
  \item $w$ = Basis weight, [kg/m$^2$]
  \item $\varepsilon$ = Effective porosity
  \item $f$ = Effective fiber volume fraction
\end{itemize}

Index

1,2 = Inlet and outlet respectively

$f$ = Fibers
Superscript

I, II = Initial and modified case respectively

REFERENCES


METHOD FOR MEASURING PERMEABILITY OF PULP SUSPENSION AT HIGH BASIS WEIGHTS
Method for Measuring Permeability of Pulp Suspension at High Basis Weights

P. PETTERSSON, T. WIKSTRÖM and T.S. LUNDSTRÖM

During the formation of pulp to paper, a large amount of water is added to dilute the pulp in order to obtain a homogenous material. This water can be mechanically and/or thermodynamically removed by different process solutions. The pulp suspension flows through various process equipment that influence the pulp suspension by changing its properties before the pulp suspension finally becomes paper. It is important to understand the mechanisms behind the transport path of water in this process in order to reduce cost and to increase the production rate of pulp and paper. The resistance to flow must be known in order to describe the flow path and the corresponding pressure drop in dewatering equipment in a pulp mill. For networks with a complex geometry, a reliable method is to measure the resistance to flow at discrete points and to fit suitable resistance models to the results obtained. The objective of this study is to investigate how the history of pulp suspensions affects their permeability. A device for measuring the permeability of various pulp suspensions at high basis weights is developed and validated. Then the permeability of a number of virgin pulp species is measured. Some of the suspensions are then circulated in a closed flow loop and permeability is measured as a function of the number of loops. The results from two separate tests show that a basis weight variation and a different process treatment of the pulp suspension do not influence permeability.

INTRODUCTION

During the formation of pulp to paper, a large amount of water is added to dilute the pulp in order to obtain a homogenous material. The water is then mechanically and/or thermodynamically removed by different process solutions. To reduce cost and to increase the production rate of pulp and paper overall it is important to understand the mechanisms behind the transport path of water. Removal of water has, in recent decades, become an important topic to understand. Researchers have studied the effect of compressing the fibre network towards dewatering plates with and without felts. Wahlström and Asklöf [1,2] have studied the removal of water by conducting a press study with felts, and many of their conclusions are still valid assumptions. The main objective of their study was to investigate the factors governing water removal and the moisture distribution of a suction press. The governing material parameters when considering removal of water are the permeability and compressibility of the suspension [3,4]. In addition to the solid load, the fibre network is exposed to a drag force generated by the flow. The magnitude of this force is dependent on how easily the fluid can flow through the network, which is commonly described by permeability. The solid load response, in turn, is often expressed with the compressibility of the fibre network. The compressibility effect of the fibre network becomes more pronounced when surface
weight increases. Higher surface weights are more likely to be found in the pulp mill, e.g. in the washing, rather than in the paper machine. For a quantitative analysis of the compression part of the web, the capillary and rheological properties must be known. A thorough knowledge of the capillary structures of the web at different degrees of compression is thus necessary for a proper understanding of pressing.

The resistance to flow must be determined in order to describe the flow of water and the corresponding pressure gradient in a press nip in the pulp mill. For networks with a complex geometry, a reliable method is to measure the resistance to flow at discrete points and to fit suitable resistance models to the results. Measurements of the resistance to flow of porous materials are, however, not straightforward. To start with, water flow through porous media does not always follow Darcy’s law. There are at least two possible reasons for this.

First, in many cases the Reynolds number becomes too high and inertia effects must be considered. The inertia effect is usually dealt with by using the Forchheimer Equation [5,6] which may be written:

\[
\frac{\Delta P}{L} = \frac{1}{K} + \beta d \rho g v^2
\]

where \( \rho \) is the pressure, \( \nu \) the superficial velocity, \( \mu \) the viscosity, \( K \) and \( \beta \) are the parameters of the porous media, and \( \rho_d \) is the fluid density. If \( \beta \) is set equal to zero, \( K \) becomes equal to the permeability \( k \) and the Darcy equation is found. Hence, in order to use Eq. (1), two material parameters must be determined.

Secondly, besides inertia effects, the pressure drop caused by the flow rate may overcome fibre mat stress; the fibre mat may deform. This phenomenon has been shown to result in a linear pressure velocity relationship up to a certain pressure difference, while above this pressure the velocity remains constant as the driving pressure is increased [7,8].

Several methods for the experimental assessment of the permeability tensor have been proposed since the first experiments by Darcy, [3,9–14]. Most of the methods are based on one of the two fundamentally different principles:

- **Parallel flow**, by which the liquid is made to flow in a controlled direction through the porous sample, i.e. the Darcy experiment.
- **Radial flow**, by which the liquid is injected at a ‘point’ and flows freely in all directions (usually in a plane). Either of these principles may be applied in a variety of ways, e.g. by pumping the liquid at a constant flow rate or at a constant pressure drop. Parallel flow measurements can be carried out under steady state conditions [13]. One drawback of this method is that porosity, and consequently permeability, differs near the walls of the cell as compared to the porosity in the rest of the bulk. Another drawback is that errors in permeability values are obtained if the flow is not in the main permeability directions. Yet another approach to determining permeability and often applied to fibrous material is to use dynamic compression equipment [15]. The fibrous network response is known in these kinds of experiments and permeability can be determined from the hydro-dynamical pressure drop according to the Tezaghi’s principle [3,4]. However, one uncertainty in this kind of experiment is that the volume fraction in the suspension is not generally constant in the dewatering direction [8,16], especially when considering the basis weights found in pulp mills.

Several permeability models for pulp suspension can be found in the literature, among others is the experimental work conducted by Lindsay [10] and Vomhoff [4]. Neither of them tested permeability at basis weights of 1 kg/m² or higher even though Lindsay measured permeability at a basis weight that was almost 10 times higher than Vomhoff. The Kozeny-Carman equation Eq. (2) gives poor agreement with the permeability of pulp suspensions especially at high porosity values, as was found in the work of Lindqvist [10] and Vomhoff [4]. Nei ther of them tested permeability at basis weights of 1 kg/m² or higher even though Lindsay measured permeability at a basis weight that was almost 10 times higher than Vomhoff. The Kozeny-Carman equation Eq. (2) gives poor agreement with the permeability of pulp suspensions especially at high porosity values, as was found in the work of Lindqvist [10] and Vomhoff [4]. Neither of them tested permeability at basis weights of 1 kg/m² or higher even though Lindsay measured permeability at a basis weight that was almost 10 times higher than Vomhoff. The Kozeny-Carman equation Eq. (2) gives poor agreement with the permeability of pulp suspensions especially at high porosity values, as was found in the work of Lindqvist [10] and Vomhoff [4]. Neither of them tested permeability at basis weights of 1 kg/m² or higher even though Lindsay measured permeability at a basis weight that was almost 10 times higher than Vomhoff. The Kozeny-Carman equation Eq. (2) gives poor agreement with the permeability of pulp suspensions especially at high porosity values, as was found in the work of Lindqvist [10] and Vomhoff [4]. Neither of them tested permeability at basis weights of 1 kg/m² or higher even though Lindsay measured permeability at a basis weight that was almost 10 times higher than Vomhoff. The Kozeny-Carman equation Eq. (2) gives poor agreement with the permeability of pulp suspensions especially at high porosity values, as was found in the work of Lindqvist [10] and Vomhoff [4]. Neither of them tested permeability at basis weights of 1 kg/m² or higher even though Lindsay measured permeability at a basis weight that was almost 10 times higher than Vomhoff. The Kozeny-Carman equation Eq. (2) gives poor agreement with the permeability of pulp suspensions especially at high porosity values, as was found in the work of Lindqvist [10] and Vomhoff [4].

\[
K = \frac{1}{a} [S_0^2 \times \varepsilon^2 (1 - \varepsilon)^2 + (1 - C_2)(1 - \varepsilon)^2]^{-1}
\]

In this equation the empirical parameters \( C_1 \) and \( C_2 \) have the values 3.5 and 57, respectively. However, the porosity in their study was based on the free liquid porosity outside the fibres. This kind of approach is only valid in the low consistency area in an actual press sequence. In the high consistency region, the fibres deform themselves and the porosity within the fibres decreases as well. Vomhoff [4] and Lindsay [10] have considered the total porosity of the fibre suspension and their model is therefore valid throughout the total pressing sequence.

In the present study, a permeability definition based on Darcy's set-up is validated against known results of pulp suspension and a porous bed consisting of spheres. The permeability of beds of spheres has been modeled by Rumpf and Gupte [17] yielding the following expression as long as the Reynolds number, Re, is reasonably low. They have shown that Darcy's law was valid for Re less than 10:

\[
K_s = \frac{D^2 \rho g v^2}{5.6 \cdot S}
\]

Permeability is given as a function of the diameter of the spheres, \( D \), the porosity of the bed, \( \varepsilon \), and a shape factor \( S \) where \( S = 1.00 \) for a narrow distribution and 1.85 for a wider distribution. To demonstrate the capacity of the device, the effect of the history of the pulp suspension on permeability is investigated for several pulp suspensions.

**MATERIAL**

Permeability measurements were conducted on a reference material of expandable polystyrene (EPS) spheres and the pulp suspension of three types of wood species: Eucalyptus Globulus, baled and re-pulped hardwood Kraft pulp that is denoted BHK pulp, a mixed tropical hardwood, baled and re-pulped hardwood Kraft pulp that is denoted BMTH and the third was a mixture of Scandinavian spruce/pine. Two different batches were used: one never dried pulp suspension and one baled pulp suspension which are denoted SBSS and SBBSK, respectively. The pulps originated from Brazil, Indonesia and Sweden, respectively. All tested pulps were fully bleached. The results performed on the EPS material were compared with the results found by Rumpf and Gupte [17]. Differences in the size and shape of the spheres are attributable to the manufacturing processes of the material.

**Reference Material**

The EPS material was provided by Styrochem located in Finland and has the following advantages as a reference material: i) its permeability is in the same range as the fibre network at high porosity; ii) it is stable under testing conditions; and its permeability can be estimated by analysis. The polymer is made of styrene containing potassium as a blowing agent. An image analysis was performed in order to estimate the diameter of the spheres by examining them in a microscope connected to the software Image pro plus. The mean diameter of the spheres was determined to 0.62 mm with a resolution of about 47 pixels per mm, Fig. 1, and the standard deviation was measured to 0.131 implying that the correction factor for a wide distribution does not apply, cf. Eq. (4). The automatic categorization of single spheres was accomplished by setting a threshold value for the roundness of the spheres to:
In this equation, \( S \) describes the perimeter and \( A \) denotes the cross-sectional area of the spheres, respectively. Hence, for a perfect spherical particle, the roundness value is 1.0. The included particles in the analyses were close to being spherically (circular in the 2D image) shaped. Hence, clusters of more than one particle were excluded from the analyses. The robustness of this method was tested by changing the roundness value from 1.1 to 1.5. The result was that the maximum variation of the diameter of the spheres was only 0.8%.

Porosity can be determined using a variety of methods [18]. In this case the volume inside the cavity is known. The EPS material was consequently put into the cavity and the void volume was filled with water at room temperature. The specimen was stirred with a stick, enabling trapped air inside the specimen to be removed while the cavity was filled with water. The void volume was then obtained by measuring the amount of water added to the cavity.

Pulp Suspension

The geometrical parameters of the fibres in the pulp suspensions were measured with the commercial image processing equipment Kajaani Fibrelab, Table 1 [19]. The resolution of the image obtained was about 1 \( \mu \text{m} \) per pixel for determining the fibre width and 10 \( \mu \text{m} \) per pixel for determining the fibre length and 10 \( \mu \text{m} \) per pixel, for determining the length of the fibre. This procedure was repeated after the permeability measurements and no significant change in geometrical parameters could be determined.

It is important to determine the porosity of the pulp suspension of the bed of spheres. This is not straightforward since the fibres themselves are porous, Fig. 2. There are at least two approaches to determining the fraction pore space for a material with double-scale porosity such as wood fibre suspensions. One approach is to only take into account the space between the fibres and to treat the pores within the fibres as solid material. This approach is used in [6,20–21] according to:

\[
\varepsilon_p = 1 - \frac{\frac{V_{fw} + V_{fl}}{V_{li}} + V_{lu}}{V_{li} + V_{lu}}
\]

where \( \varepsilon_p \) stands for the effective porosity of the pulp suspension, the fibre wall volume is represented by \( V_{fw} \), the free volume between the fibres by \( V_{fl} \) and the lumen volume inside the fibres by \( V_{lu} \). The different volumes are illustrated in Fig. 2. The advantage of this strategy is that at high porosity the effective porosity describes the actual volume where the fluid will flow. However, in dewatering equipment the pulp suspension often reaches low porosities and the fibres start to deform and the free volume outside the fibres decreases towards zero. Consequently, this approach is not usable at low porosity. In this case it is better to use the total porosity as suggested by Lindsay [10] and Vomhoff [4]. The porosity is then determined using the density method [18]:

\[
\varepsilon_t = 1 - \frac{\rho}{\rho_f}
\]

where \( \varepsilon_t \) stands for the total porosity of the pulp suspension, \( \rho \) is the density of the pulp suspension, and \( \rho_f \) is the density of the fibre material.

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Average fibre width, ([\mu m])</th>
<th>Length weighted average fibre length, ([mm])</th>
<th>Weight weighted average fibre length, ([mm])</th>
<th>Arithmetic average fibre length, ([mm])</th>
<th>Coarseness value, ([mg/m])</th>
<th>Fibre Curl, [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>24.40</td>
<td>2.25</td>
<td>2.78</td>
<td>1.59</td>
<td>0.159</td>
<td>16.3</td>
</tr>
<tr>
<td>2</td>
<td>26.15</td>
<td>2.26</td>
<td>2.85</td>
<td>1.44</td>
<td>0.146</td>
<td>12.2</td>
</tr>
<tr>
<td>4</td>
<td>16.10</td>
<td>0.91</td>
<td>1.06</td>
<td>0.76</td>
<td>0.069</td>
<td>13.7</td>
</tr>
<tr>
<td>5</td>
<td>15.60</td>
<td>0.80</td>
<td>0.88</td>
<td>0.715</td>
<td>0.059</td>
<td>17.8</td>
</tr>
<tr>
<td>6</td>
<td>15.60</td>
<td>0.80</td>
<td>0.88</td>
<td>0.715</td>
<td>0.060</td>
<td>17.5</td>
</tr>
</tbody>
</table>

The fibre length is defined as the true length of the fibre along thecentreline.
where $v$ is the basis weight, $h$ is the thickness of the pulp suspension, and $\rho_f$ is the fibre wall density. This equation for porosity will be used hereinafter in this report.

**EXPERIMENTAL**

To experimentally derive the permeability of the pulp suspension, a permeability measurement unit was developed and designed for measurements of out-of-plane permeability. The cavity had an inner diameter and a maximum stroke length of 0.1 and 0.3 m, respectively.

The device was designed to let a pressure-driven flow of water pass through the specimen, in the vertical direction from bottom to top, Fig. 3. The fluid entered and exited the measuring cell through permeable walls and distribution plates were placed on each side of the permeable walls.

The permeability measurements of the pulp suspension were conducted at stationary conditions, i.e., a constant flow rate was applied throughout the pulp suspension while the height of the cavity was held constant. The Re number was much less than unity, typically in the order of 0.0001. For the EPS spheres the measurements were conducted at a flow rate that was as low as possible with respect to the pressure drop, i.e., Re < 1.7.

Since the permeability of the pulp suspension is strongly dependent on porosity, additional measurements were performed by decreasing the thickness of the pulp pad. This procedure was repeated until the lowest possible volume of the cavity was reached, with respect to the limit of the pressure transducer or until the maximum load from the hydraulic press that was used to compress the suspension was achieved.

Permeability was determined using Darcy's law by integrating Eq. (8) in the flow direction and by assuming a homogeneous porosity profile:

$$\frac{dp}{dx} = -\frac{\mu}{K} \left(\frac{Q}{A}\right)$$

Fig. 3. A schematic picture of the permeability measurement system.

The permeability measurements of the pulp suspension were conducted at stationary conditions, i.e., a constant flow rate was applied throughout the pulp suspension while the height of the cavity was held constant. The Re number was much less than unity, typically in the order of 0.0001. For the EPS spheres the measurements were conducted at a flow rate that was as low as possible with respect to the pressure drop, i.e., Re < 1.7.

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Permeability was determined using Darcy's law by integrating Eq. (8) in the flow direction and by assuming a homogeneous porosity profile:

$$\frac{dp}{dx} = -\frac{\mu}{K} \left(\frac{Q}{A}\right)$$

where $v$ is the superficial velocity, i.e. the total flow rate divided by the cross-sectional area, $\mu$ is the dynamic viscosity of the fluid, $K$ represents the intrinsic permeability, and the gradient on the left-hand side is the pressure drop of the fluid through the porous material. The results from Darcy's law state a linear pressure velocity relationship as long as inertia effects can be neglected. This is true as long as Re, based on a characteristic length-scale of the material is below unity.

The fluid flow and its pressure drop over the web and the actual thickness of the web were registered by a computer, Fig. 3. The flow rate was measured with an electromagnetic flow meter DS21 made by ABB. This sensor measures a flow rate between 0–2 dm³/min, corresponding to a superficial flow velocity inside the cavity of 0–4.2 mm/s and with an accuracy of 1% of the maximum reading. The pressure drop was measured with a differential pressure gauge, a Rosemount transducer model 1151 (range of 0–11 kPa 0.05 %) while the thickness of the pulp suspension was measured with a magnetostrictive position sensor, MTS sensors, a range of 0–0.3 m ±0.08 mm. Note that the pressure drop over the dewatering plates was measured individually. It was found that the pressure drop throughout the plate in the flow range used when measuring permeability was much smaller than the pressure drop throughout the material itself. However, the pressure drop was included in the permeability measurements. The temperature of the incoming fluid was measured with a PT 100 sensor with an accuracy of 1%. The temperature was measured in order to use the correct viscosity when deriving permeability.

The pressure drop over the pulp suspension, the flow through it and its thickness were measured in the measurement. A sensitivity analysis of how these parameters influenced the permeability of the pulp suspension resulted in a 1 to 1 relation, i.e., a 1% variation in each of the mentioned variables gave a 1% change in the measured permeability. Temperature, in turn, affected permeability indirectly by the viscosity of the fluid, and a first estimate is that an alteration of 1% influenced permeability by 0.5%. The total estimated error from the measurements conducted on 1 kg/m² was about 7% at a porosity of 0.5.

All pulps were re-pulped and prepared according to SS-EN ISO 5261-1:2004. The amount of pulp corresponding to the desired surface weight was placed into the measuring cavity. The pulp suspension was poured into the measuring volume with a consistency by mass of 1% to eliminate the amount of trapped air inside. At some points the differential pressure sensor did not reach the zero value of the sensor, indicating trapped air inside the suspension. At these points a flow rate was applied through the suspension until equilibrium at zero was reached. At the point where the pressure sensor had reached the equilibrium of zero the suspension was slowly compressed to the desired start consistency, about 5%.

The flow loop consisted of a pump, a dewatering press, a dilution step and a tank. The pulp was dewatered to a porosity value of about 0.6. After the dewatering process the pulp suspension was re-pumped to a porosity value of about 0.95 and run repeatedly in the loop. The pulp was removed from the system after different numbers of circulation and permeability tests were conducted.

**RESULTS**

The measurements of the bed of spheres follow Eq. (4) as well as measurements previously conducted in another device by Petersen.
son et al., Fig. 4 [22]. A maximum deviation of 6% from the theoretical models was obtained which can be regarded as a very good result since the theoretically derived permeability in itself is dependent on two independent measurements: the porosity of the bed and the image analysis of the dimensions of the spheres, Eq. (4). In addition, the total estimated error in these measurements was about 5% based on an analysis of the accuracy of the transducers and the geometry of the cell.

For the pulp suspensions a variation in Re showed only a small variation in permeability that is most likely related to systematic errors or minor stochastic variations in the measurement sensors. According to Darcy’s law, Eq. (8), permeability should be independ-
ent of the basis weight. A slight deviation from true pulp thickness due to stochastic variations strongly influenced the calculated porosity, especially at small thicknesses. This is illustrated in Fig. 5, and could be one explanation for the large scattering effect most apparent at low porosities. The measurements performed on higher basis weights (2 kg/m²) give slightly lower results. Similar results were found for BHK and SBSK pulps. The empirically determined constants for the permeability model are given in Table II.

The permeability results of the different types of pulp suspensions revealed that the permeability of the Hardwood, BHK and BMTH pulps was higher overall than the Softwood, SBSK and SBBSK, pulps especially at low porosities, i.e. Fig. 6 where the results performed by Lindsay are plotted as regression lines [10].

The number of circulations in the flow loop did not influence the pulp as illustrated in Fig. 7. The number of times the pulp was circulated in the system before it was removed is shown in the legend, i.e., BMTH 0 was not circulated at all while BMTH 2 was circulated about two times.

In addition to the process history investigation of the BMTH pulp, a morphological study was conducted on the BHK pulp, Table 1. It was shown that by circulating the pulp suspension in the circulation loop, the geometrical data of the pulp suspension did not change. Two permeability measurements were performed on the BHK pulp: a variation in basis weight and a measurement of pulp that had circulated in the flow loop, Fig. 8 where the names in the legend indicate the numbers of circulation and the actual basis weight, [kg/m²], respectively. The results indicate that neither the basis weight nor the process history influence permeability. However, the results presented for BHK 2:1 deviate from the other ones.

Finally, the measurements carried out on the SBSK pulp also indicate that its permeability is independent of the process treatment of the pulp suspension and also independent of a basis weight variation, since only small variation is noticeable, Fig. 9.

**DISCUSSION**

The objective of this study was to examine how the processing history of a pulp suspension affects its permeability. A device for measuring the permeability of various pulp suspensions at high basis weights was developed and validated. In the validation process conducted by using EPS material, a deviation of at the most 6 % from the theoretical models developed by Rumpf and Gupta was obtained [17]. This discrepancy is in the same order as the accuracy of the measuring system itself and thus the device is successfully verified.

The measurements performed on SBBSK, SBSK and BHK pulp with a basis weight variation indicate that permeability is independent of the basis weight. This is true except for one measurement of the BHK pulp that showed an overall higher permeability, Fig. 8. Determining permeability, especially of a pulp suspension, demands an extremely accurate experimental procedure. Such a methodology was applied here but nevertheless errors may occur. One explanation for the deviation that is more likely than others is related to the closing procedure. If the volume is decreased too quickly when reducing porosity then internal channels can be created. Such channels may form in the fibre network if the hydrodynamic pressure is higher than the local network stress of the pulp suspension. The consequence of this is that a permeability that is too high is ob-
tained. A high pressure drop may also, on a more global level, affect permeability. At a certain level the pressure drop overcomes network stress and the assumption of a constant porosity profile is not valid, consequently a permeability that is too low is obtained. Having a constant flow rate this effect is most pronounced at high basis weight and as shown in the measured porosity range, the permeability was independent of a basis weight variation. This fact indicates that the pressure drop in the measurements was small enough so that no compression of the fibre bed occurred during the permeability measurement.

The geometry of the individual fibres may change when drying pulp suspensions since the fibre wall can collapse which would influence the overall permeability of the network. However, the permeability measured was virtually independent of the number of loops which was confirmed by the fact that the morphological data obtained was almost unaffected by the number of loops. Permeability is a geometrical parameter describing the ease with which a fluid can flow through a porous network, and if the geometry of the individual fibres is not changed, then permeability should also be unchanged. A summary of the permeability measurements showed that the history of a pulp does not affect its permeability, and that the deviation was considered to be systematic errors rather than being related to the geometrical change in the fibres. However, there are huge differences in the dewatering ability of the pulp suspensions in the dewatering processes depending on what the pulp has been exposed to. This change in behavior must, according to our results, be related to the solid phase of the material, i.e. a change in the suspensions’ yield stress. Subsequently, a forthcoming study will focus on the compressibility effect of the pulp suspension in order to understand the dewatering phenomenon.

ACKNOWLEDGEMENT

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NOMENCLATURE

\( K \) Permeability [m²]
\( \mu \) Dynamic viscosity [Pas]
\( R \) The Roundness value
\( \rho \) Density of the fluid [kg/m³]
\( \rho_f \) Fibre wall density [kg/m³]
\( S \) Specific length [m]
\( S_p \) Shape factor for the porous material
\( v \) Superficial fluid velocity [m/s]
\( V_f \) Fibre wall volume [m³]
\( V_l \) Free liquid volume [m³]
\( V_n \) Lumen volume of the pulp suspension [m³]
\( w \) Basis weight [kg/m²]
\( x \) Distance in flow direction of the permeability cell [m]

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KEYWORDS: WOOD FIBRE, POROSITY, PERMEABILITY, PULP SUSPENSION.
DEVELOPMENT OF MATERIAL MODELS FOR DEWATERING OF PULP SUSPENSIONS
DEVELOPMENT OF MATERIAL MODELS FOR DEWATERING OF PULP SUSPENSIONS

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ABSTRACT

During the process of making pulp from wood, free fibers are mixed in a pulp suspension containing a large amount of water (98-50% by mass), wood fibers and often some processing chemicals. The suspension in this process is gradually cleaned from dissolved material. The suspension can be washed in a displacement washing step where the dirty fluid is replaced with a cleaner one, or by a compression step which increases the consistency of the suspension. To reduce costs and to increase the production rate of pulp and paper overall it is important to understand the interaction between fluid and fibers in such processes. During dewatering and washing, fibers are exposed to a drag force from the fluid. As the concentration of fibers increases this drag force becomes proportional to the permeability of the fiber network formed. When contact between fibers increases, an additional pressure emanates caused by bending and compressing of the fibers. By comparing experiments to a numerical model this study shows that for high dewatering velocities the resulting force required to dewater a suspension cannot be found by adding these two pressures. One reason for this may be that intra-fiber flows contribute to the force. Another explanation can be related to reinforcement of the network, i.e. when compressing the network an inertial effect occurs. This effect can explain the observed time scale in the measurements.

INTRODUCTION

Pulp suspension is a mixture of a large amount of water, wood fibers and often some chemicals. To reduce costs and to increase the production rate of pulp and paper overall it is important to understand the mechanisms behind the transport of water in these processes. Dewatering has been an important topic of research in recent decades with the purpose of reducing cost and improving quality in the paper-mill industry. (Wahlström 1960) and (Asklöf, Larsson et al 1964) have studied the removal of water by conducting a press study with felts, and many of their conclusions are still valid assumptions. The main objective of their research was to investigate the factors governing water removal and the moisture distribution of a suction press. To be able to forecast and understand the dominating factors when dewatering a pulp suspension, the interplay between fluid and fibers must also be understood. To begin with, it is obvious that fibers are exposed to a drag force generated by fluid during dewatering and washing. As the concentration of fibers increases this drag force becomes proportional to the permeability of the fiber network formed. This permeability describes the ease with which a fluid flows through a porous medium, such as a fiber network, and is defined in Darcy's law according to

\[ \frac{dp}{dx} = \frac{\mu \cdot u}{k} \]  

where \( p \) is the pressure, \( \mu \) is the dynamic viscosity of the fluid, \( u_s \) is the superficial relative velocity of the fluid inside the fiber network and \( k \) represents the permeability of the porous medium (Ingmansson, Andrews et al 1959), (Lundström, Toll et al 2002) and (Vomhoff 1998). When contact between fibers increases during dewatering, an additional pressure appears that is caused by the fibers being bent and compressed (Toll 1998). This pressure, termed here \( P_s \), is related to the compressibility of the fiber network and has been derived for a couple of idealized arrangements in (Toll 1998) to yield the following equation

\[ P_s = cE(\phi^0 - \phi) \]  

where \( c \) and \( n \) are constants dependent on the geometry of the network, the variable \( E \) is the modulus of the fibers, \( \phi \) is the solid volume fraction and the subscript 0 denotes initial conditions.

The total force generated during pressing is thus shared by the fluid and solid fibers ((Vomhoff 1998), (Lobosco and Kaul 2001), (Szikla and Paulapuro 1989) and (El-Hosseiny 1991)). By using the Therazaghis principles, which state that in all layers, i.e. in the direction of the hydraulic pressure gradient in a suspension, the applied pressure must be split between fluid and solid pressure, (Grén and Hedström 1967), (Martinez 1998). This relationship is simply described in the following manner

\[ P = P_f + P_s \]  

This equation states that hydraulic and solid pressures can be measured separately to obtain the total pressure. The validity of this assumption will be investigated in this study.
Hydrodynamic pressure is determined by using knowledge of the permeability of a specific material. The permeability of pulp suspensions has been reported in an experimental study conducted by Pettersson et al. (2008), Fig. 1. This permeability model is based on Ingmansson, Andrews et al (1959). Their research focused on determining permeability by describing fibers as solid tubes that were non-deformable, since porosity in the study was based on the free liquid volume outside the fibers. This model is based on the liquid both outside and inside the fibers, i.e. the total porosity,

$$k = \left( B_1 S_0 \cdot \varphi^{3/2} \left( 1 + B_2 \cdot \varphi \right) \right)^{-1}.$$  \[4\]

In this equation, $B_1$ and $B_2$ are empirical constants, $S_0$ describes the specific surface of the material and is defined as $4/d$, where $d$ is the mean diameter of the fibers. The geometrical parameters of the fibers in the pulp suspensions were measured with the commercial image processing equipment KajaaniFiberlab (2004). The mean diameter of the fibers was determined to be 24.4 µm.

Experimental

Experiments were conducted in a compressibility apparatus where pulp could be dewatered at different speeds and the resulting force could be measured; see Fig. 2 for a schematic sketch. All experiments were performed on Scandinavian fully bleached kraft pulp from the Östrand mill in Sundsvall, Sweden. The pulp suspension was disintegrated using a standardized method according to ISO5263-1:2004. The slurry was then formed manually with a spoon in a cavity in the compressibility apparatus, Fig. 2, the spoon was used to flatten and distribute the pulp as evenly as possible. The cavity had a diameter of 0.1 m and a maximum height of 42 mm. The initial properties of the pulp suspension and experimental settings are shown in Table 1. A hydraulic piston was attached to an MTS Multipurpose TestWare, which corresponds to a specific surface pressure of 127 bar with a ±80 mm stroke. A constant compression velocity was applied to the permeable piston. This was continued until maximum load of the press was achieved, i.e. 100 kN. This was performed several times for each pulp suspension with speeds from a few mm/s up to about 8 mm/s in order to investigate the influence of compression velocity on the dewatering ability of the pulp suspension. The data generated was recorded with a logger MTS FlexTest II with the MTS 793.00 system software ver. 3.3b, while the control monitoring program MTS Multipurpose TestWare was used to collect the data, i.e. the actual position and the load applied to the static impermeable wall as a function of time. The drain plate had an open flow area of about 19 % in the form of a number of holes, each with a diameter of 1 mm.
The force generated to maintain constant velocity during dewatering is strongly dependent on the position of the piston, as well as velocity. Hence, it is extremely important to know the compliance of the total system, including the measurement volume, in order to describe the correct average solidity. This is particularly important towards the end of the compression trial, when the load is the largest while pulp pad thickness is the lowest. The total applied force influences the surrounding system including the distance gauge, i.e. it is by all means necessary to take into account the compliance of the system. For example, the total load, in many cases, caused a strain in the system close to as much as 0.2 mm. Consequently, the signal from the position sensor was corrected by the compliance of the system.

Table 1. Experimental conditions. The initial concentration by weight was aimed at 5 %. The pulp was a baled and fully bleached pulp from the Östrand mill in Sundsvall, Sweden.

<table>
<thead>
<tr>
<th>Test no.</th>
<th>Compression speed [m/s]</th>
<th>Basis Weight [kg/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.97E-6</td>
<td>1.02</td>
</tr>
<tr>
<td>2</td>
<td>2.49E-4</td>
<td>2.04</td>
</tr>
<tr>
<td>3</td>
<td>4.99E-4</td>
<td>2.01</td>
</tr>
<tr>
<td>4</td>
<td>9.95E-4</td>
<td>2.04</td>
</tr>
<tr>
<td>5</td>
<td>1.99E-3</td>
<td>2.08</td>
</tr>
<tr>
<td>6</td>
<td>3.99E-3</td>
<td>2.05</td>
</tr>
<tr>
<td>7</td>
<td>7.98E-3</td>
<td>1.94</td>
</tr>
</tbody>
</table>

RESULTS

The pressure as a function of porosity was derived for quasi-static conditions and experimental data was fitted to [2] resulting in an $R^2$ value of 0.97. Deviation occurred at high pressures. In order to obtain better correspondence, the data was fitted to the following expression, see solid line in Fig. 3.

$$P_s = \frac{C_1 \cdot \phi^{C_2}}{1 - \phi^{C_3}}$$

where $C_1$, $C_2$, and $C_3$ are the empirical constants for this specific pulp suspension. The empirical parameters are 3.11e6 [Pa], the other two are dimensionless 2.56 and 3.18, respectively, and $\phi$ denotes solidity. Notice that if $C_1$ and $C_2$ are small, [2] and [3] are practically equal. However, in the current case, the constants resulting from the curve fitted to an $R^2$ value of 0.99 imply that $C_1$ attains a value close to three, thus indicating the need to take into account additional mechanisms to those modeled by Toll (1998). It is also obvious that the higher the velocity of the piston, the higher the pressure generated at a given porosity, i.e. compare Table 1 and Fig. 3.

Fig. 3. Results of the total applied pressure in the measurements. The required pressure increases with compression velocity at all porosities.

EXPERIMENTAL MODELLING

A time scale could be detected in all the experiments, since a higher compression speed generated a higher-pressure load for a certain porosity value. In line with the static solid pressure function, this time scale must be entirely captured by the hydrodynamic term. The pressure build up was studied using a tool developed in Matlab, where Equations [1], [3], [4] and [5] were applied. The modeling was based on an Eulerian two-phase model including continuity, where fluid and fibers represent the two phases.

The system was too weak at low speeds. This was noticeable since the simulations did not follow the build up pressure in the experiments. However, when the compression velocity was increased further the modeled pressure over-predicted the measurements as in case 7, see Fig. 4. This can be interpreted as meaning that the permeability model and subsequently the alteration in geometry of the fiber network are not valid for higher velocities. Consequently, results indicate that describing 1D compression of a pulp
suspension requires a system that captures more than one time scale.

![Graph showing porosity and permeability comparison between simulations and experiments.](image)

Fig. 4. Simulation of a 1D compression test using both permeability and a static solid pressure function.

**DISCUSSION**

Results from the simulations showed that the response from the simulations was too weak at moderate velocities. One reason for this could be that fluid inertia is not included in the modeling. However, Pettersson, Lundstrom et al. (2006) showed that up to $Re$ of 10 inertia effects can be neglected while $Re$ in the compressibility experiments is lower than 1 according to

$$Re = \frac{\rho \cdot v \cdot L}{\mu} \Rightarrow Re \leq 1.$$ \[6\]

This implies that a time scale must be related to the solid network stress model. Hence, it is likely that the deformation of the solid network, i.e. the rearrangement of the fibers, is dependent on the speed of the deformation. A low compression velocity was applied when determining the compressibility model for pulp suspension. The fiber mat was exposed to a compression that gave a counter-force that corresponded to a certain time scale. When increasing compression speed, it can be expected that a rearrangement of the fibers will require a higher force as discussed by Buscall and White (1987).

Another explanation for the difference between model and experiments is, as described by Lobosco and Kaul (2001), that the solid pressure term at some stage becomes dependent on the flow of fluid out from the fibers. If this is true, an extra term must be added to the solid pressure function. This term should function as a viscous damper, i.e. a velocity-dependent parameter that causes a higher resistance to network deformation when velocity is increased.

In case 7 where simulations over-predicted the measurement, one explanation could be that if the pressure drop over the fluid phase in the in-plane direction is larger in magnitude than the yield-stress of the pulp suspension, channels may be introduced into the system. This can occur close to the dewatering plate with an open area of 19 % with holes of 1 mm each. Consequently, the dewatering resistance drastically decreased with a corresponding decrease in the hydrodynamic pressure drop. This can be expected to cause a modification in the expression of the permeability of the system since the solidity in the in-plane direction drastically changes. This phenomenon could clarify the discrepancy between the simulation and the experiment in case 7, where a shift in results occurred.

To determine which of the above phenomenon dominates compression measurements an experiment should be set up where force, position and consistency profile can be measured at the same time.

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INSIGHT INTO THE PRESSURE FILTRATION OF SOFT PARTICLE SUSPENSIONS
Insight into the Pressure Filtration of Soft-Particle Suspensions

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Abstract

The filtration of papermaking fibers has been studied in which a cellulose fiber network deforms dynamically under action of an external load. The described network consists of hollow, flexible rod-like particles more or less saturated. During filtration, initially there is a reduction in pore volume and an increase in the number of fibers in contact. Due to the shape of the fibers the network can be described as bimodal, considering the differences in pore scale between the lumen and the free volume outside the fibers. Previous results on filtration of papermaking fibers have indicated that there is a lag in the system, i.e. a rate dependency. In this work we tackled this by assuming that when the fiber-fiber interaction is increased the flow in the small pore scale becomes important. Here we modeled this process by considering that the energy required to compress the network must balance the viscous dissipation rate of the small pore scale by the use of a dynamical compressibility of the network. Closure equations were developed and tested experimentally by comparison to the pressure developed to drive the piston. Good agreement was found between the prediction of the build-up pressure up to a compression speed of 8 mm/s. The valid length scale for viscous dissipation on the meso scale was found in this work to be twice the fiber length.

Key words: Fluid Mechanics; Porous Media; Filtration; Modelling; Papermaking

To be submitted
1 Introduction

The filtration of a concentrated flocculated suspension operated under a constant rate of compression is investigated. Although this work is motivated from a Pulp & Paper application, this class of problem has received considerable attention in the literature as it has widespread industrial and theoretical importance. The focus of this work is with suspensions in which the particles interact with each other mechanically to give rise to a local particle pressure $p_s$, which is the effective stress tensor. One of the remaining difficulties with such classes of suspensions is that during filtration, densification of the suspension may occur by both a reduction of the interparticle spacing and by deformation of the individual particles themselves. This leads to an additional complication in describing the local particle pressure as the compression is governed by mechanisms which act at on different geometrical and time scales.

Before we discuss the pertinent models relevant to pressure filtration of this class of material, it is instructive to review the properties of one particular suspension following such behaviour. One example of this is a papermaking fibre suspension. Papermaking fibres are hollow, flexible rod-like particles which have a wide distribution in both length and diameter depending upon species and growing conditions (see Figure 1). Papermaking fibre suspensions typically aggregate into coherent networks which possess measurable mechanical strength (Bennington & Kerekes, 1996; Gullichsen & Härkönen, 1981; Kuznetsov et al., 1995; Scott et al., 1999). The reviews of Jokinen & Ebeling (1985); Kerekes et al. (1985); Powell et al. (1996) and the references contained therein summarize our current knowledge of fibre suspension rheology. Although fibre networks may form by surface charges, Mason (1954) found that mechanical entanglement rather than colloidal force was the principle source of fibre flocculation. They entangle, bend, and remain networked from frictional forces transmitted by fibres that are locked into bent configurations (Meyer & Wahren, 1964). Soszynski & Kerekes (1988) confirmed the influence of bending stresses on floc strength through stress relaxation experiments. A number of research groups estimate that under typical processing conditions there are, on average, 3-4 interfibre contacts (Dodson, 1996; Meyer & Wahren, 1964). This physical make-up leads to complex rheological behavior with the suspensions showing strong stress/strain-rate relationships. The major feature of the stress/strain-rate relationship is that of an inelastic non-Newtonian fluid.

Once networked, the suspension takes on the property of a (somewhat) solid structure. In particular compressive stresses on the suspension can be transmitted via the network and the structure has the ability to support itself. If stressed by an external force, say for example by a weight, the network stress $p_n$ will resist this force until it deform irreversibly. The traditional term to describe this process is the compressive yield stress $P_y(\phi)$, where $\phi$ is the lo-
cal solidity, and has been measured by a number of authors for papermaking suspensions and generally follows equations of the form

\[ P_y = m \phi^n \]  
\[ P_y = m \frac{\phi^n}{(1 - \phi)^p} \]

(1)  
(2)

\( m, n, \) and \( p \) are empirical constants that must be determined from experiment (Han, 1969; Wilder, 1960; Wrist, 1964). Similar expressions have also been derived by analysis of the bending of individual fibres showing that atleast the first expression above has a micro-mechanical basis (Toll, 1998).

\[ P_y = CE(\phi^n - \phi_0^n) \]

where \( n \) in this case is theoretically derived for different arrangement of fibres, \( E \) is the Yong’s modulus of the fibres, \( C \) is a variable dependent on the fibre arrangement and the subscript 0 indicates initial conditions. The exact mechanism by which the network deforms under load remains an open question. However, during uniaxial compression, initially there is a reduction in pore volume, an increase in the number of fibres in contact and bending of the fibres (Toll, 1998). At some degree of compression, the number of fibres in contact is such that further compression can only occur by the individual fibres themselves through deformation of the fibre wall. In other words, the large hollow central region of the fibre must collapse. If saturated, the rate of collapse of the cell wall is dictate by the rate by which the fluid can drain from the intra-fibrillar region through the inter-fibrillar space. A schematic of
this is illustrated in Figure 2. It is now argued that this process is somewhat similar to a classic lubrication mechanism in which a viscous fluid is moving through a narrow but variable gap. As the two surfaces of the lumen collapse, the elevated lubrication pressures causes drainage of the fluid and elastic deformations in the fibre wall material. This mechanism is strikingly different than the pressure filtration process of say colloidal particle suspensions for which many of the mathematical models are currently available and also an additional mechanism to those studied in (Toll, 1998).

In this work we examine the pressure filtration of a concentrated papermaking fibre suspension. In §2 a one-dimensional model for a cylindrical filter press will be established for this class of suspension using a volume averaged eulerian-eulerian approach. The analysis will follow closely previously presented filtration models for a colloidally stable suspension, e.g. (Landman et al., 1991), but an additional kinetic expression to describe the kinetics of consolidation will be included. This expression is similar in form to that posed originally by Buscall & White (1987) for consolidating colloidal particles settling in a centrifuge. We will argue that the process in our case is strikingly different than that posed Buscall & White (1987), the form of the resulting equation however is quite similar. Like Buscall & White (1987) a function is introduced, termed the "dynamic compressibility" which in effect describes the lag between the application of a force and the response of the network - this function will be related somewhat crudely to physical parameters in the system. In §4, we attempt to confirm the form of this model through measurements of the pressure required to filter a papermaking fibre suspension at a prescribed piston displacement rate. Finally, a comparison of the model predication and the experimental measurements are made in §5.
2 Development of the Dewatering Model

A one-dimensional pressure filtration model is developed for this class of soft flocculated suspensions. Historically, the research effort in pressure filtration and gravity thickening, which are very similar unit operations, have been both substantial and protracted and the model presented here is closely based on this literature (Auzerais et al., 1988, 1990; Buscall & White, 1987; Concha & Bascur, 1977; Concha & Bustos, 1986; Landman et al., 1991; Shirato et al., 1977; Sivaram & Swamee, 1977; Terzaghi & Peck, 1948; Usher et al., 2001; Wakeman et al., 1991).

The analysis is limited to estimating the pressure $\sigma(t)$ required to maintain a constant rate filtration $u_c$ of a dilute papermaking suspension at an initial solidity of $\phi_0$. As we are only concerned with a concentrated suspension, we consider that the initial solidity is greater than the gel concentration. Landman et al. (1991) indicates that there are a number of other modes of operation. The model presented here may be recast to cover this more general case but this is beyond the scope of this work as the intention is to demonstrate the utility of the approach outlined.

Consider a filtration event in which a filter is located at $x = 0$ and the domain extends upwards to a piston located at $x = h(t)$; $h_0$ is the initial height (see Figure 3). The suspension fills this domain and is drained under the pressure $\sigma(t)$. 

Fig. 3. A sketch of the compression cell used in the filtration events.
generated as the piston moves towards the filter. Plug flow is assumed and solidity of the suspension does not vary significantly over its cross-section. Conservation of particles and fluid masses requires that

\[
\frac{\partial \phi}{\partial t} + \nabla \cdot (\phi \mathbf{u}) = 0 \tag{4}
\]

\[
\frac{\partial (1 - \phi)}{\partial t} + \nabla \cdot [(1 - \phi) \mathbf{w}] = 0 \tag{5}
\]

where \( \mathbf{u} \) and \( \mathbf{w} \) are the velocities (vector quantities) of the particles and fluid. The volume fraction (or solidity) of the particle phase is denoted by \( \phi \) and is defined as the ratio of volume of the fibres to its total volume. In the force balance equations, as argued by Landman et al. (1991) essentially the hydrodynamic drag forces will balance the pressure gradients and as a result, the equations of motion reduce to

\[
0 = -\phi \frac{\partial p}{\partial x} \mathbf{\hat{x}} - \phi \frac{\partial p_s}{\partial x} \mathbf{\hat{x}} - \mu \frac{(1 - \phi)}{k(\phi)}(\mathbf{u} - \mathbf{w}) \tag{6}
\]

\[
0 = -(1 - \phi) \frac{\partial p}{\partial x} \mathbf{\hat{x}} + \mu \frac{(1 - \phi)}{k(\phi)}(\mathbf{u} - \mathbf{w}) \tag{7}
\]

where \( p \) is the fluid pressure; \( \mu \) is the viscosity of the fluid; and \( k(\phi) \) is the permeability of the particle network.

There are various experimental methods for determining \( k(\phi) \), Lundström et al. (2000). Most of these methods simply involve the measurement of the superficial flow rate of the fluid for a given pressure drop. Perhaps the most comprehensive study of the permeability of various porous materials has been done by Jackson & James (1986). For concentrated papermaking fibre suspensions the characteristic permeability \( k_c \sim 10^{-12} \text{ m}^2 \). This is by all means a rough estimate and there is a vast literature where more accurate estimates can be found (Carlsson, 1983; Ellis, 1981; Han, 1969; Ingmanson et al., 1959; Lindsay, 1990; Ljungkvist, 1983; Meyer, 1962; Nilsson & Larsson, 1968; Robertson & Mason, 1949; Vomhoff, 1998). However as the concentration increases great efforts must be spent on the experimental procedure (Lundström et al., 2002; Pettersson et al., 2008b). One reason to this is that \( k(\phi) \) is strongly dependent on the porosity of the fibre network.

Finally, in the force balance equations we have neglected the inertial, gravitational, and shear stress terms and before proceeding we attempt to justify this assumption by examining the order of magnitude of these stresses. If we set the largest inertial term to be \( \rho u_c^2/h_o \), and the viscous term to be \( \mu u_c/h_o^2 \), we can show that this model is valid only when
\[ Da = \frac{k_e}{h_o^2} \ll 1 \] (8)

\[ Re Da = \frac{\rho_u h_o k_e}{\mu h_o^2} \ll 1 \] (9)

where \( Da \), and \( Re \) are the Darcy and Reynolds numbers.

At this point we attempt to consider the dynamics of the compression event and consider that the fibre network requires time to respond to changes in an external load. Our argument stems from the fact that this "lag" results from fluid being expressed from the intraparticle space through the external voidage through a small pore. We model this process through use of an energy conservation equation. Here we assume that the energy dissipation on the network is equal to the viscous dissipation generated by fluid flowing through a small pore. The basis for this argument is given by Buscall & White (1987) and the wording and logic presented below follows this reference quite closely.

To begin, consider a volume element \( V \) of networked suspension at a volume fraction \( \phi \) subject to an external network load \( p_s \) large enough to cause collapse of the local network. The network itself is capable of resisting this pressure by generating internally an opposing pressure \( p_y(\phi) \). The net work done in increasing the volume fraction by an amount \( d\phi \) is

\[ dW = - (p_s - p_y(\phi)) dV = V (p_s - p_y(\phi)) \frac{d\phi}{\phi} \] (10)

With this we see that the rate of doing work on the system can be estimated using

\[ \frac{dW}{dt} = \frac{V}{\phi} (p_s - p_y(\phi)) \frac{d\phi}{dt} \] (11)

We assume that most of this work is dissipated in the fluid as it flows through a pore. To estimate the viscous dissipation, we assume that the fluid escapes through a number of pores of length \( \ell \) and radius \( r_o \). With Hagen-Poiseuille flow, the velocity field \( v \) in a single pore is given by

\[ v = \frac{\hat{p}}{4\mu} (r_o^2 - r^2) \] (12)

The viscous dissipation rate per unit volume at the wall of the pore is \( \mu \left( \frac{dc}{dt} \right)^2 \) and the total dissipation rate in the volume element is therefore
Equating the viscous dissipation rate to the rate of doing work on the system Equation 11 yields

$$\frac{d\phi}{dt} \approx \frac{1}{\lambda(\phi)} (p_s - p_y(\phi))$$

where

$$\lambda(\phi) = \frac{4\mu\ell^2}{r_o^2\phi}$$

At this point we need to make further assumptions regarding the dimensions of the pore. As permeability in a very broad sense is a measure of the characteristic area of a pore, we set $r_o^2 \sim k(\phi)$. The characteristic length of the pore is difficult to ascertain and as a first approximation we argue that this term must be related to some characteristic length of the particle itself, say its length or cell wall thickness. As we are uncertain of the proper length scale we set this to be $\ell \sim \sqrt{\delta H_o/2}$, where $\delta$ is an empirical parameter which we will determine subsequently by experiment. We choose the to make $\ell$ proportional to $H_o$ as this is the maximum length scale in our system. It should be noted that we divide this result by two to help simplify the notation. With this we anticipate that $\delta$ is bounded between zero and $\sqrt{2}$. In essence we do so to eliminate the four in Equation 15. With this, the dynamic compressibility of the network is given by the form

$$\lambda(\phi) = \delta \frac{\mu H_o^2}{k(\phi)\phi}$$

The argument presented here indicates that when the characteristic radius of the pore is small in comparison to the path length of the fluid, i.e. $k(\phi)/H_o^2 \rightarrow 0$, the dynamic compressibility function becomes very large. This indicates that the network responds very slowly to changes in the applied force. This is the case we feel represents the dynamics of filtration event studied here. In the opposite sense, when the path length is very small in comparison radius of the pore, the dynamic compressibility function is very small implying that $p_s \approx p_y(\phi)$. Physically we interpret this to mean that the suspension densifies immediately with an externally applied force. This scenario was the case originally considered by Buscall & White (1987) where colloidal stable suspensions of “hard” particles were filtered under pressure. Like Buscall & White (1987) we write Equation 14 in the general form
\[ \frac{D\phi}{DT} = \frac{1}{\lambda(\phi)} [p_s - p_y(\phi)] \quad p_s \geq p_y(\phi) \]  

(17)

Here, \( D/DT \) is the material derivative. Although the true functional form of the dynamic compressibility is difficult to ascertain \textit{apriori}, in this paper we will test Equation 15, through the solution of Equations 22 through 24, by comparison to experimental data.

Following the algebraic manipulations and reasonings given Landman \textit{et al} (1991), if

\[ u = -u\dot{x} \quad w = -w\dot{x} \]  

(18)

the governing equations reduce to

\[ \frac{\partial \phi}{\partial t} = \frac{\partial}{\partial x} (\phi u) \]  

(19)

\[ \frac{\partial p_s}{\partial x} = \frac{\mu}{(1 - \phi)k(\phi)} (u - u_c) \]  

(20)

\[ \frac{\partial u}{\partial x} = \frac{1}{\phi\lambda(\phi)} [p_s - p_y(\phi)] \]  

(21)

All that remains at this point are the initial and boundary conditions. At time \( t = 0 \), we assume that \( \phi \) is constant throughout the cylinder. This implies that

\[ \phi(x, 0) = \phi_0 \]  

(22)

The particle velocity satisfies

\[ u(0, t) = 0 \]  

(23)

\[ u(h(t), t) = u_c \]  

(24)

as no particles move through the filter membrane at \( x = 0 \) and the particles move with the velocity of the piston at \( x = h(t) \). In addition to this at \( x = 0 \), the network stress \( p_s \) must equal the applied pressure \( \sigma(t) \), i.e.

\[ p_s(0, t) = \sigma(t) \]  

(25)

if the flow resistance of the filter membrane is small. Details of this latter expression are explained in further detail by Landman \textit{et al} (1991). In essence, this expression stems from the fact for the assumptions used in the analysis, the sum of the fluid and network pressures, that is \( p \) and \( p_s \), must equal the applied pressure \( \sigma \) at every elevation in the filtration device. In this paper we
will consider that \( h(t) \) is a known function and is given by \( h(t) = h_o - u_c t \). With this Equations 22 through 24 can be solved directly and then used to estimated the applied pressure through use of Equation 31.

Before proceeding, it is instructive to scale these equations. We do so by introducing the characteristic scales

\[
t_c = \frac{h_o}{u_c} \quad p_c = \frac{\mu u_c h_o}{k_c} \quad k_c = k(\phi_o)
\]

and scaling the dependent and independent variables using

\[
U = \frac{u}{u_c} \quad T = \frac{t}{t_c} \quad P_s = \frac{p_s}{p_c} \quad X = \frac{x}{h(t)} \quad \Sigma = \frac{\sigma}{p_c}
\]

In addition to this, if functions are scaled using

\[
K(\phi) = \frac{k}{k_c(\phi_o)} \quad P_y(\phi) = \frac{p_y}{m} \quad H = 1 - T \quad \phi \Lambda(\phi) = \frac{1}{K(\phi)}
\]

and the following dimensionless parameter is introduced

\[
\epsilon = \frac{p_c}{m}
\]

the governing equations reduce to

\[
\frac{\partial}{\partial T} (\phi H) = \frac{\partial}{\partial X} (\phi (U - X)) \quad (26)
\]

\[
\delta \epsilon \frac{\partial}{\partial X} \left[ K(\phi) \frac{\partial U}{\partial X} \right] = \epsilon \frac{H}{(1 - \phi)K(\phi)} (U - 1) - P_y'(\phi) \frac{\partial \phi}{\partial X} \quad (27)
\]

Subject to

\[
\phi(X, 0) = \phi_o \quad (28)
\]

\[
U(0, T) = 0 \quad (29)
\]

\[
U(1, T) = 1 \quad (30)
\]

Once this system has been solved, the pressure required to drive the piston can be determine using

\[
\Sigma(T) = \frac{\delta}{K(\phi)} + 1 \frac{\epsilon}{\epsilon} P_y(\phi) \quad (31)
\]
3 Solution of the Dewatering Model

In the section we solve Equations 26-27 in two different manners. In the first method we approach the problem using asymptotic methods and solve the problem in the limit of $\epsilon \to 0$; this case represents the slowly moving piston where $u_c \approx 0$. Here we seek a series solution using a regular perturbation expansion. In the second approach the solution is solved numerically using a second-order accurate finite difference method. Finally we confirm the validity of the solution by comparing the numerical solution to the asymptotic solution.

We begin the asymptotic solution by formally stating that we seek a solution to the problem using a solution of the form

$$\phi = \phi_0 \left( \phi^{(0)} + \epsilon \phi^{(1)} + \ldots \right)$$  \hspace{1cm} (32)

$$U = U^{(0)} + \epsilon U^{(1)} + \ldots$$  \hspace{1cm} (33)

under the condition that $\delta \sim O(1)$. With this Equations 26-27 reduce to the following sets of equations

1. **Zeroth order approximation:**

   $$\frac{\partial}{\partial T} \left( \phi^{(0)} H \right) = \frac{\partial}{\partial X} \left( \phi^{(0)} (U^{(0)} - X) \right)$$  \hspace{1cm} (34)

   $$\frac{\partial \phi^{(0)}}{\partial X} = 0$$  \hspace{1cm} (35)

2. **$O(\epsilon)$:**

   $$\frac{\partial}{\partial T} \left( \phi^{(2)} H \right) = \frac{\partial}{\partial X} \left( \phi^{(0)} U^{(2)} + \phi^{(2)} (U^{(0)} - X) \right)$$  \hspace{1cm} (36)

   $$\delta \frac{\partial}{\partial X} \left( K(\phi^{(0)}) \frac{\partial U^{(0)}}{\partial X} \right) = \frac{H}{(1 - \phi^{(0)}) K(\phi^{(0)})} \left( U^{(0)} - 1 \right) - \ldots$$  \hspace{1cm} (37)

The solution procedure follows along the usual lines. Here we solve the zeroth order problem and then substitute these results into the $O(\epsilon)$ system of equations. With this the composite solution of the problem is given by
\[ \phi = \frac{\phi_0}{H} \left( 1 + \epsilon \frac{H}{D(\phi^0)} \left( \frac{1}{2} X^2 - X + \frac{1}{3} \right) \right) + O(\epsilon^2) \]  
\[ U = X \left( 1 + \epsilon \left( \frac{1}{6} X^2 - \frac{1}{2} X + \frac{1}{3} \right) \frac{H}{\phi_0} \frac{d}{dT} \left( \frac{\phi^0 H^2}{D(\phi^0)} \right) \right) + O(\epsilon^2) \] (38)  
(39)

The function \( D \) is defined by

\[ D(\phi) = (1 - \phi)K(\phi)P'_y(\phi) \] (40)

The first observation that can be made from this solution is that to the lowest order of approximation, there are no spatial gradients in concentration and the velocity field varies linearly in \( X \). To reiterate, the case solved using this approach represents the situation the slowly moving piston, that is \( u_c \to 0 \), and the results on an intuitive basis seem physically realistic. Secondly, we observe that to this order of approximation the solution is independent of \( \delta \). This result we found somewhat surprising. However, if the series is extended to include the \( O(\epsilon^2) \) approximation, we do indeed find that both \( \phi \) and \( U \) are dependent on \( \delta \). Thirdly, under the assumption that \( \epsilon \to 0 \), we anticipated boundary layer type behavior as a small parameter multiplied the highest derivative in Equation 27. What we found is that the regular perturbation series used is uniformly valid for all values of \( X \). In other words the solution for \( U \) satisfies the boundary conditions and no boundary layer behavior is apparent. This latter point was confirmed as we performed a singular asymptotic solution in the region \( X \to 0 \).

At this point we continue and report the numerical method used to solve Equations 26-27. This system is solved using second order accurate in both time and space finite difference scheme. The method is briefly summarized below

1. Equation 26 is solved using the two-step Lax Wendroff method. In the first step in this procedure we define an intermediate value of \( \phi_{n+1/2} \) at half time steps \( T_{n+1/2} \) and the half mesh points \( X_{j+1/2} \) by advancing Equation 26 explicitly using the Lax scheme.

\[ \phi_{j+1/2}^{n+1/2} = \frac{1}{2} \left( \phi_j^{n+1} + \phi_j^n \right) - \frac{\Delta T}{2\Delta X} \left( F_{j+1}^n - F_j^n \right) \] (41)

where \( F = \phi(U - X) \); and \( \Delta X \) and \( \Delta T \) are the difference between adjacent nodes spatially and temporally, respectively.

2. At the half mesh points, the value of \( U_{j+1/2} \) is updated by solving Equation 27 as a two-point boundary value type problem using MATLAB’s built in function \texttt{bvp4c}. The current value of \( \phi_{j+1/2}^{n+1/2} \), which was determined using the explicit Lax method presented in the previous step, was used in this calculation.
With the updated values for $U$ and $\phi$ at the half mesh points, the fluxes $F_{j+1/2}^{n+1}$ at the half mesh points can now be determined more accurately. With this, we use the second step in the Lax-Wendroff method and estimate the value for $\phi_j^{n+1}$ at the nodal points, explicitly, with a properly centered difference expression which is second order accurate in time. In our notation this is given by

$$\phi_j^{n+1} H^{n+1} = \phi_j^n H^n + \frac{\Delta T}{\Delta x} \left( F_{j+1/2}^{n+1/2} - F_{j-1/2}^{n+1/2} \right)$$

At the mesh points, the value of $U_j$ is updated by solving Equation 27 using the same boundary value method.

The applied pressure $\Sigma$ can now be determined using Equation 31.

To validate our numerical method a number of simulations were performed and compared to the asymptotic solution under the condition that $\epsilon \to 0$ and $\delta \sim O(1)$. The numerical work compared quite well to the asymptotic solution.

4 Experimental Details

Experiments were conducted in which the force required to dewater a papermaking fibre suspension was measured at a constant displacement rate. All experiments were performed on Scandinavian fully bleached baled softwood pulp from the Östrand mill in Sundsvall, Sweden. The pulp suspension was disintegrated using a standardized method according to ISO5263-1:2004. The cavity of the apparatus was then filled with the suspension and then flattened manually in order to distribute the pulp as evenly as possible. The cavity had a diameter of 0.1 m and a maximum height of 42 mm. The initial properties of the pulp suspension and experimental settings are shown in Table 4. A hydraulic piston was attached to an MTS 312.21 load frame with a maximum load of $\pm 100 \, kN$, which corresponds to a specific surface pressure of 127 bar with a $\pm 80 \, mm$ stroke. A constant compression velocity was applied to the permeable piston. This was continued until maximum load of the press was achieved, i.e. $100 \, kN$. This was performed several times for each pulp suspension with speeds from a few mm/s up to about 8 mm/s in order to investigate the influence of compression velocity on the dewatering ability of the pulp suspension. The data generated was recorded with a logger MTS FlexTest II with the MTS 793.00 system software ver. 3.3b, while the control monitoring program MTS Multipurpose TestWare was used to collect the data, i.e. the actual position and the load applied to the static impermeable wall as a function of time.

Finally, for closure of the model predictions, two experimentally determined functions are required. The compressive yield stress $p_y$ has been measured for
Table 1
The experimental conditions tested

<table>
<thead>
<tr>
<th>uc (mm/s)</th>
<th>o</th>
<th>ho (mm)</th>
<th>ε</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>0.25</td>
<td>0.06</td>
<td>20.1</td>
</tr>
<tr>
<td>b</td>
<td>0.50</td>
<td>0.06</td>
<td>20.5</td>
</tr>
<tr>
<td>c</td>
<td>1.0</td>
<td>0.06</td>
<td>23.1</td>
</tr>
<tr>
<td>d</td>
<td>2.0</td>
<td>0.06</td>
<td>22.3</td>
</tr>
<tr>
<td>e</td>
<td>4.0</td>
<td>0.05</td>
<td>26.6</td>
</tr>
<tr>
<td>f</td>
<td>8.0</td>
<td>0.05</td>
<td>27.1</td>
</tr>
</tbody>
</table>

this particular pulp previously (Pettersson et al., 2008a), that is

\[
p_p(\phi) = m \frac{\phi^n}{(1 - \phi)^p}
\]

where \(m = 3.1 \text{ MPa, } n = 2.6, \) and \(p = 3.2\). Pettersson et al. (2008b) have shown that the permeability of this particular fibre suspension follows an expression similar to that reported by Ingmanson et al. (1959), i.e.

\[
k(\phi) = \frac{a}{\phi^{1.5}} \left( \frac{1}{1 + b\phi^3} \right)
\]

where \(a\) and \(b\) are empirical constants determined by Pettersson et al. (2008a).

5 Results and Discussion

In this section we present the results in two subsections. In the first part of the discussion we examine the comparison between the model and the experimental data with the assumption that there is no "lag" between the application of force and densification of the network. In essence we set \(\delta = 0\). Here, we will show that there is a systematic difference between the model predictions and the experimental data. In the second part of the discussion, we solve the model equations and estimate \(\delta\).

To begin, we compare the model results to the experimental results by eliminating the effect of lag. To do so we set \(\delta = 0\) and then eliminate \(P_s\) from the governing equations. The implications of this assumption are that densification of fibre network occurs instantaneously as the pore length is small. The
implications of this is that $P_s$ is always equals the equilibrium value of $P_y$. After some algebraic manipulations, Equations 26 - 27 reduced to

$$H(T)^2 \frac{\partial \phi}{\partial T} = \frac{1}{\epsilon} \frac{\partial}{\partial X^2} (D(\phi)\phi) + (1 - X)H(T) \frac{\partial \phi}{\partial X}$$

subject to

$$\phi(X, 0) = \phi_0$$

$$\frac{\partial \phi}{\partial X}(0, T) = -\epsilon H(T) \frac{\phi}{D(\phi)}$$

$$\frac{\partial \phi}{\partial X}(1, T) = 0$$

It should be noted that this system is exactly the same as that defined by Landman et al. (1991). This system of equations were solved using MATLAB built-in command pdpde compared to the data. It should be noted that no fitting parameters are required for this prediction. The result is shown in Figure 4. The first observation that can be made from this figure is that the difference between the model and the experiments increases with increasing rate of the piston. In fact, the error is quite large as at 8 mm/s, see Figure 4f, as the $y$-axis is logarithmic. The second observation is that the model under predicts the experimental results consistently. Clearly under this assumption, the model performs quite poorly.

At this point, we are convinced that a "lag" does exist in the system and the magnitude of the "lag" is rate dependent. Equations 26 - 27 were now solved under an assumption for the free parameter $\delta$. Here we set $\ell$ to equal twice the length of a fibre or $\delta = 0.15$. A comparison of the experimentally measured profile with the prediction is given in Figure 5. What is evident is that the behavior of the model resembles the experimental data quite well.

6 Conclusions

As mentioned a "lag" exists in the system implies that a time scale is introduced when describing the behavior of the system during filtration. This effect must be related either by the solid part or by the fluid part inside the fiber network or by both. Considering the fluid, it can introduce inertial effect from the fluid when flowing through the network, since when compacting the network, fluid flow generates out from the network. However, the flow speed in this work corresponding to a Re number much less than unity. In the work presented by Pettersson et al. (2008b) shows that the linearity between the
Fig. 4. A comparison of the experimental data (markers) with the prediction (dashed line) given for the condition $\lambda = 0$. The data is shown in six subplots representing each of the experimental conditions: (a) $u_c = 0.25 \text{ mm/s}$; (b) $u_c = 0.50 \text{ mm/s}$; (c) $u_c = 1.0 \text{ mm/s}$; (d) $u_c = 2.0 \text{ mm/s}$; (e) $u_c = 4.0 \text{ mm/s}$; and (f) $u_c = 8.0 \text{ mm/s}$.

The pressure drop and the fluid flow is valid at least up to a Re number of 2, i.e. the Darcy approach is valid up to $\text{Re}=2$. Hence, the "lag" must be fiber related.

One effect that describes the lag is related to the rearrangement of the fibers during compaction. At low compaction rates it is expected that the inertial effect of rearrangement of the fibers are low, hence, by measuring the compressibility of a material the inertial response to rearrange is capture, Pettersson et al (2008a). At higher compression rates the rearrangement effect must be expected to be more pronounced. The rearrangement effect of the network must be considered to be the dominating part especially at low solidity values where the fiber-fiber interaction are exposed to only a few contact
points and solely the fibers is not expected to be fully clamped to each other. Eventually when the fiber-fiber interaction is increased and the fibers can be expected to be more or less fully clamped to each other, a further compaction of the network must be entirely due to compaction of fibers itself. The latter described compaction of the network must be considered not to relate to the rearrangement of the network, at that position the rearrangement effect must due to that be negligible compared to other effects occurred inside the network. The described network consists of hollow, flexible rod-like fibers more or less fully saturated. Due to the lumen volume of the fibers the network can be described as a bimodel, considering the differences in pore scale. When the fiber-fiber interaction consists of only a couple of contact points all pores are
still communicating. However when the fiber-fiber interaction is increased the mechanics to flow is fully contolled by the small pore scale.. This mechanics is more pronounced when the compression rate is large. Hence, the ”lag” can due to that be coupled to the flow inside the lumen volume generated by the collapse of fiber in the network. When the solidity is increased the fiber-fiber contact will increase and eventually the lumen volume will start to decrease too. This effect is supported by Lobosco et al (2005) which showed similar results in their work. Hence, this ”lag” is controlling the collapsibility of the fiber network, and should due to that be coupled to the morphology of the fibers itself. Hence, the energy required to compress the network was assumed to be balanced by the viscous dissipation rate. The viscous dissipation in the macro scale is described by use of Darcy approach where the length scale is set to the dewatering length, however the valid length scale for the viscous dissipation for the miso scale is found in this work to be twice the fiber length.
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