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# MODELLING OF MECHANICAL DEWATERING IN CONTACT WITH ROUGH PERMEABLE SURFACES

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## ABSTRACT

A model of the mechanical dewatering process during wet pressing was formulated that includes a non-uniform compaction at the interface between web and felt. This non-uniform compaction is assumed to be caused by the surface roughness of the felt. The model of the simultaneous deformation and flow in the fibre network was implemented in ABAQUS, a general finite element system. The dewatering behaviour of different rough permeable surfaces, representing model-felt surfaces, was investigated. Results obtained with the model showed the influence of the felt model surface on dewatering, especially at lower grammages. Here, the non-uniform compaction leads to a considerable decrease in obtained dryness. This decrease was more pronounced for rougher felts. In addition, each felt had an optimal dewatering behaviour at a certain grammage. In general, finer model felts performed better at lower grammage, which is in agreement with practical experiences in wet pressing.

## INTRODUCTION

Compression of a water-containing deformable material against a porous object is a common mechanical dewatering process. The porous object applies load to the water-containing material, deforms it and allows its water to escape through the pores. The permeability and compressibility of both the water-containing material and the porous object are important properties for the dewatering efficiency.

Wet pressing of paper is an example of such a process. Water is removed from the fibre web by pressing it against a permeable object, the press felt. A picture of a paper web compressed against a press felt shows that the load is applied unevenly to the paper surface (Figure 1). Some parts of the paper are not in contact with the felt. Consequently, no press force is transmitted to those parts of the paper by the felt. This effect is relevant for industrial wet pressing, as many studies have shown the influence of felt surface roughness on the achievable dryness [1–6]. In general, smoother felts gave a better dewatering of low grammages webs.

Vomhoff [7] has presented a hypothesis assuming that the press forces, locally applied by the batt fibres on the surface of the press felt, are spread in the paper web in a wedge-like manner. This hypothesis represents a simplification of the general load spreading from a point-wise or line-wise applied load, a standard problem in solid mechanics. The non-uniform compaction of the web results in a boundary effect, termed "interaction layer", with uncompressed and compressed web areas adjacent to the felt. By showing that the steady-state permeability of the fibre web depends significantly on the grammage and on the coarseness of the contacting surface, Vomhoff

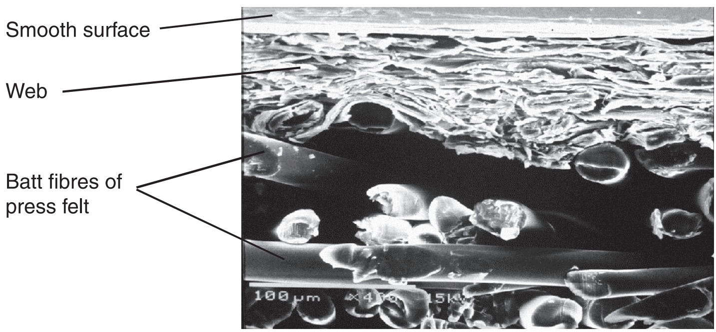


**Figure 1** Fibre web compressed between a smooth impermeable roll surface and the batt fibres on the surface of a permeable wet pressing felt (image by Beloit).

corroborates the existence of this boundary effect [8]. I'Anson and Ashworth [6] have presented a wet pressing theory based on the same concept.

A number of quantitative models of wet pressing have been proposed in the literature. A review of the work before 1990 is presented by El-Hosseiny [9]. New models have been proposed later by Kerekes and McDonald [10–13], Kataja et al. [14, 15], Bloch [16, 17], Riepen [18] and Gustafsson et al. [19].

None of these models takes the influence of non-uniform compaction and flow in the interaction layer into account. To our knowledge, the only models doing that are those of Andersson [20] and Chau [21]. Andersson has modelled the local flow in a fibre web with a prescribed structural pressure profile in the vicinity of a batt fibre. Chau has modelled the non-uniform deformation in a fibre web caused by batt fibres in a periodic configuration. This model did not consider the water flow.

There is clearly a lack of models taking both deformation and water flow into account. Consequently, in the present study, ABAQUS [22], a general finite element system, was used to implement a mathematical model for the dewatering of a fibre web that was compressed non-uniformly at the interface between felt and web.

## DESCRIPTION OF THE MODEL

### Model of the felt surface

Some simplifying assumptions have been made in order to reduce the size of the model and the required time for its computation: The paper was assumed saturated in all parts of the press nip; the batt fibres of the model felt were arranged in a periodic two-dimensional manner and the batt fibres were assumed rigid and impermeable. The structure of the model, implemented as a finite element model for the calculation of a single-felted press nip, is depicted in Figure 2.

For a double-felted press nip configuration the situation is more complicated. Batt fibres on the two sides of the paper appear in a random manner. In some places a batt fibre on one side of the paper is opposed by a void in the other felt; in other places it is opposed by a batt fibre. The angles between batt fibres on the two sides are also random. The overall interaction of the two felts is thus a combination of many random contact situations. Calculation of these cases requires a three-dimensional model which is beyond the scope of this work. In this study, the two extreme cases of completely aligned and completely interspersed batt fibres in a two-dimensional periodic configuration were considered. Figure 3 shows the different felt configurations used in this model study.

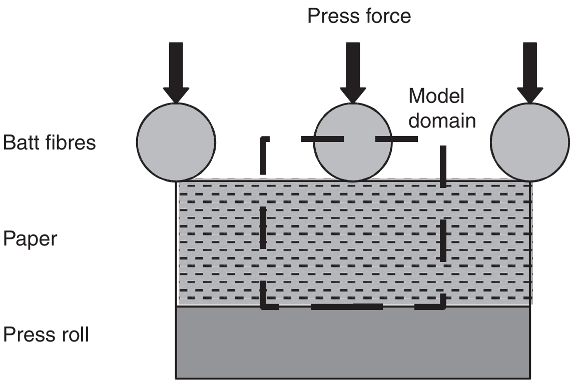


**Figure 2** The structure of the wet pressing model implemented as finite element model for a single-felted press nip.

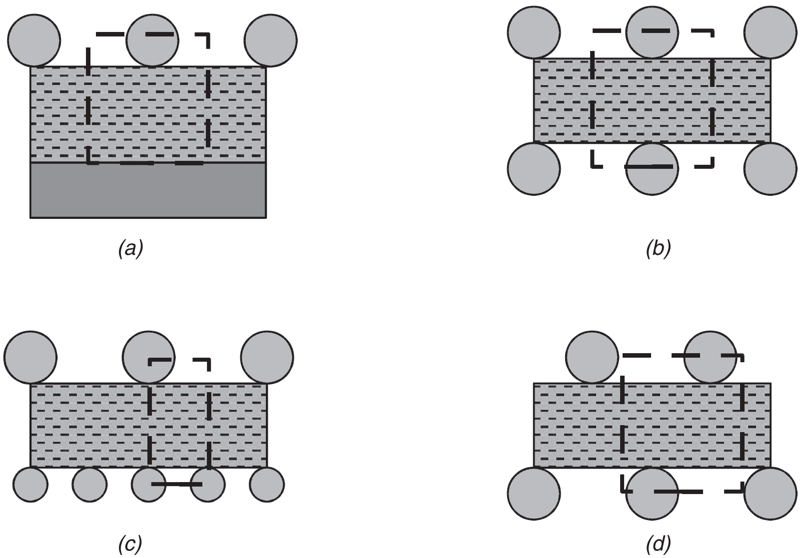


**Figure 3** Model geometries for different felt configurations; (a) single-felted, (b) double-felted, aligned and identical batt fibre diameters, (c) double-felted, coarse and fine batt fibres,(d) double-felted, interspersed and identical batt fibre diameters.

The ABAQUS model was used to calculate the dewatering in a press nip with different press felt model surfaces and grammages. It calculated the local deformation and water flow in the paper web in a representative cross-section. Due to the assumed periodicity and in some cases symmetry of the press felt model surface, it was sufficient to calculate only a small part of the cross-section, the area that is designated "model domain" in Figure 2 and shown in Figure 3.

## Numerical model

The numerical model for wet pressing presented here is based on the formulation for porous media in the ABAQUS Finite Element System [22]. It is based on the principle of effective stress. The web is assumed saturated during the whole pressing operation. It is also assumed that water bound to the fibre wall cannot be pressed out. Thus, in the model, the bound water was considered part of the solid. For a saturated porous medium without trapped fluid, the effective stress principle states that the total stress is the sum of the effective stress of the fibre network and the pressure stress of the fluid:

$$\sigma = \sigma_e - p \cdot \mathbf{I} \tag{1}$$

where $\sigma$ is the total stress tensor, $\sigma_e$ is the effective stress tensor, $p$ is the fluid pressure and $\mathbf{I}$ is the identity matrix. This formulation of the effective stress principle also assumes that Terzaghi's principle is applicable.

## Assumptions

Although ABAQUS is a very general finite element code some simplifying assumptions were made in order to reduce the amount of work by avoiding the effort of writing user defined elements and material models. These simplifications were not minor and are expected to reduce the model accuracy. However, the model still provided a good qualitative description of the mechanisms involved in wet pressing when taking the influence of the rough felt surface into account.

The contact area between the fibre web and the felt has a very complicated shape. In addition, the contact area between felt and web increase with increasing applied stress. The detailed description of the contact was however beyond the scope of the work. The contact situation between the felt and the web was therefore simplified. All batt fibres were assumed to be parallel in an arbitrary direction in the plane of the web. Then it was assumed that all batt fibres were equally spaced and that the distance between the fibres did not depend on the applied load. From Gullbrand's measurement [23], a mean value of the contact area ratios, i.e. the ratio between projected batt fibre area and the total area, was calculated to 40.5% and used in all model calculations. Furthermore, the batt fibres were assumed to be rigid and impermeable.

In a real press nip the load from the roll is applied gradually and two points in the nip with different positions in the machine direction have identical load curves but shifted in time. The present periodic model configuration covers a very small part of the distance along the press nip, justifying that the small time shift is neglected. Thus, the load in the periodic model could be applied simultaneously along the press nip. This simplification is equivalent with an assumption that only local in-plane flow, on the length scale of the model domain, can occur.

The constitutive relationships for the fibre web are best modelled as a non-linear time-dependent material with a permanent deformation, as described by Lobosco [24, 25]. In the present model, this was simplified in the following way: The fibre web was assumed to be a non-linear elastic continuum modelled as an elastomeric foam; all Poisson's ratios and shear strains were neglected; the time-dependence of the network stress is neglected which means all time-dependent stresses are ascribed to the water flow through the fibre web. The in-plane stresses are assumed to have two components: the elastomeric foam stress in tension, which is low, and an additional linear elastic tensile stress physically explained by the stretching of the fibres, that are mainly oriented in the in-plane direction of the web.

**Boundary conditions**

The model domain of the fibre web has four boundaries. In the case of a single-felted press nip, one of the boundaries is the contact with the roll. It was assumed impermeable both to fluid and fibres. All points on this boundary had the same vertical motion. The in-plane boundaries were periodic boundaries. The displacements were identical at these boundaries and fluid exiting one boundary appeared at the other. In some cases these boundaries were arranged in a symmetric way. In these cases, there was no horizontal displacement and no flow across the boundary. The web-felt boundary was partially in contact with one or more batt fibres, which were assumed impermeable. The points of these boundaries that were in contact with batt fibres could only slide along its surface. This motion was assumed to be frictionless. The other points on these boundaries were free and the hydraulic pressure at these points was zero.

In the case of a double-felted press nip, there was batt fibres on both sides of the web and consequently both out-of-plane boundaries were permeable except for the areas that were in contact with the batt fibres.

## MATERIAL PROPERTIES

### Fibre web out-of-plane compressive resistance

Following Chau [17] the out-of-plane elastic deformation was modelled as an elastomeric foam. In the general case, the behaviour was based on a strain energy function including thermal strains, ABAQUS [22]. In this implementation there were no thermal strains and the Poisson's ratios were neglected. In the simplest case the strain energy function had one term, which was used here for the out-of-plane fibre web stress:

$$\sigma_w = \frac{2\mu}{e^{\varepsilon}\alpha}(e^{\alpha\varepsilon} - 1) \tag{2}$$

where $\varepsilon$ is the logarithmic strain, $\sigma_w$ is the out-of-plane stress in the fibre web; $\mu$ and $\alpha$ are material parameters. Suitable values for the parameters were calculated from Vomhoff's dynamic network compression experiment [26]. A plane-press experiment on an MTS-equipment with a softwood bleached kraft pulp web with a pulse length of 25 ms and a peak stress of 22 MPa was selected. Selecting a short pulse of a similar length as the simulated press pulse partially compensated for the lack of time-dependency of the material model. A curve fit gave values for $\mu$ and $\alpha$ of 0.178 MPa and –2.19, respectively.

For very high web compressions less water is pressed out of the pore space outside the fibre wall. Instead, water is pressed out of the fibre walls in order to increase the dryness further. The water content will eventually approach the bound water content of the fibres and no further mechanical dewatering is possible unless very excessive pressure is applied. At this point the stiffness of the web was assumed to increase to the stiffness of solid fibre wall material. Chau [21] has determined the tensile stiffness index in MD for dry paper of the same grade as was used here. From that value an average Young's modulus of the fibre material was calculated in the following way:

$$\begin{aligned} E_f &= \rho_c E^w \\ E^w &= 6.93\ \text{MNm/kg} \\ \rho_c &= 1549\ \text{kg/m}^3 \\ E_f &= 10.7\ \text{GPa} \end{aligned} \tag{3}$$

where $E_w$ is the tensile stiffness index obtained by Chau, $\rho_c$ is the density of cellulose and $E_f$ is the Young's modulus of the fibre material. This value was then assumed to apply asymptotically when the porosity approaches zero, in all directions and both in compression and tension.

The bound water content was estimated from curves published by Laivins and Scallan [27] to 0.58 kg of water per kg of cellulose. From this value and the initial dryness an equivalent strain for the bound water was calculated. The final expression for the out-of-plane stress is a sum of the elastomeric foam stress and the solid material stress active below the bound water content:

$$\sigma = \sigma_w + \sigma_b \tag{4}$$

$$\sigma_b = \begin{cases} 0 & \varepsilon > \varepsilon_b \\ E_f(\varepsilon - \varepsilon_b) & \varepsilon \leq \varepsilon_b \end{cases}$$

$$\varepsilon_b = \ln\,(v_b/v_c)$$

$$\varepsilon = -\ln(v_c)$$

where $\sigma$ is the stress, $\sigma_w$ is the stress from the elastomeric foam model, $\sigma_b$ is the stress from the bound water, $v_b$ is the volume fraction of bound water, $v_c$ is the volume fraction of the dry fibre material, $\varepsilon$ is the equivalent strain, $\varepsilon_b$ is the equivalent bound water strain and $E_f$ is the Young's modulus of the dry fibre material.

The elastomeric foam part of the out-of-plane stress was a non-linear function of the strain. For the obtained calibration, the stiffness was low for tension and small compressions (see Figure 4). For high compression the stiffness was high.

The parameters in the stress-strain relationship depended on the initial thickness of the fibre web due to the definition of strain. This meant that the calibration was valid only for compressions with equal initial dryness. The initial dryness calculated from the MTS-experiment was 13.4%. The initial dryness value in the model calculations was set to 17%, which was a mean value of the web dryness before the second press nip of STFI-Packforsk's pilot paper machine EuroFEX. Using this somewhat higher value made a comparison with dewatering experiments from this paper machine possible. The effect of this difference on the stress strain relationship was neglected.

### In-plane tensile stiffness

The forces in the paper web are transferred between the fibres through fibre bonds and tension of fibre segments. A wet fibre is like a soft, hollow string

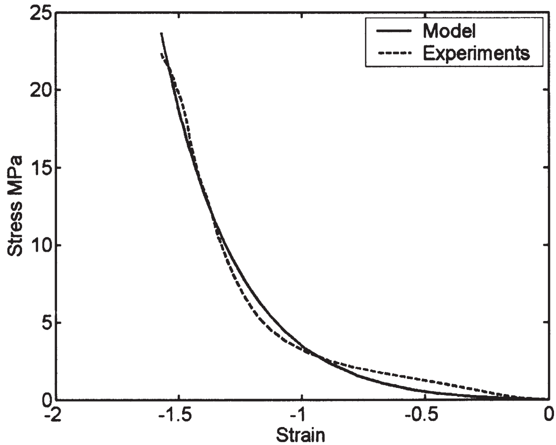


**Figure 4** Stress-strain relationship for the material model in out-of-plane direction as described by the hyperfoam model, assumed model compared with experimental work (based on data from Vomhoff [28]).

that can take a high load in tension but only a relatively small load in compression. Due to the filtration process in paper making, the fibres are mainly oriented in the plane of the paper. When the fibre network is compressed, the fibres are at first loosely bound and some movement of individual fibres relative to others is possible. When the compression increases, the fibre-fibre bonds become stronger and an increasing share of the load is transferred through tension of fibre segments. The stress transfer will then strongly depend on the axial stiffness of the fibre segments.

The elastomeric foam model was isotropic and had a low tensile stiffness. It was unable to model the high tensile stiffness of the fibre segments. The high in-plane tensile stiffness was instead modelled using one-dimensional reinforcement elements with linear elastic material properties in tension:

$$\sigma_{xt} = \begin{cases} E_t \varepsilon_x & \varepsilon_x \geq 0 \\ 0 & \varepsilon_x < 0 \end{cases} \tag{5}$$

where $\sigma_{xt}$ is the tensile stress from the fibres, $E_t$ is the Young's modulus and $\varepsilon_t$ is the in-plane strain. These reinforcement elements were superposed to the elastomeric foam model (Figure 5). To avoid problems with buckling of the reinforcement elements they took no load in compression.

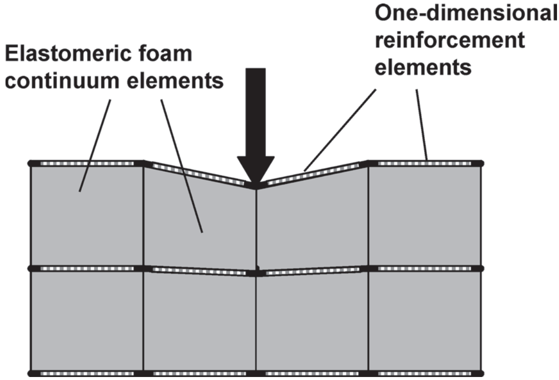


**Figure 5** Sketch of the superposition of the isotropic elastomeric foam continuum and the one-dimensional reinforcement elements.

## Permeability

The fibres in the paper web are mainly oriented in the plane of the paper, which results in different in-plane and out-of-plane permeabilities. The in-plane permeability was assumed to be isotropic. Both in-plane and out-of-plane permeabilities were assumed to depend exponentially on the porosity:

$$K(n) = K_0 e^{an} \tag{6}$$

where $K$ is the permeability, $n$ the porosity, and $K_0$ and $a$ material parameters.

The out-of-plane permeability parameters were determined from the measurements for pulp webs made from bleached softwood kraft pulp [8]. The in-plane parameter values were based on experimental data for bleached softwood kraft pulp webs [28]. The values used in the model are summarized in Table 1 and the corresponding permeability curves are shown in Figure 6.

**Table 1** Permeability model parameters.

| | $K_0$ $(m^2)$ | $a$ |
|---|---|---|
| In-plane | $6.19{\cdot}10^{-25}$ | 31.4 |
| Out-of-plane | $1.10{\cdot}10^{-28}$ | 42.3 |

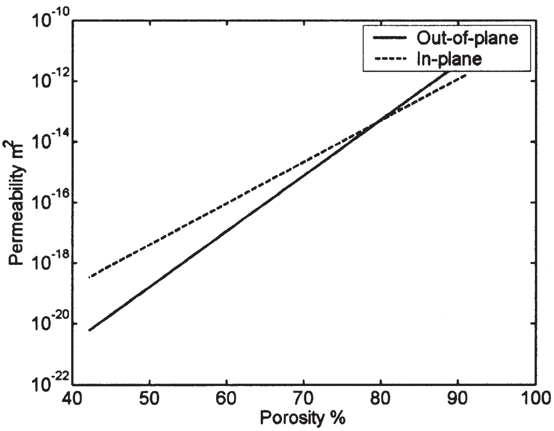


**Figure 6** The assumed out-of-plane and in-plane permeability as a function of porosity (based on measurements by Vomhoff et al. [8, 28]).

## Process conditions

The model presented here has been used to evaluate dewatering under process conditions typical for the first shoe press nip of the pilot paper machine EuroFEX at STFI-Packforsk. Felts with a surface batt fibre diameter in the range of 5 to 90 μm, single-felted and double-felted press configurations and grammages of 15 to 105 g/m$^2$ were simulated. Here, the model felt surface with a batt diameter of 5 μm represented a next to ideal smooth surface. The press pulse shape was a standard Metso shoe press pulse with a tilt of 1.0 (Figure 7). However, in the calculation, the pulse had to be stopped at the peak pressure, discarding the final pressure release, which the present model could not handle.

Results of pilot paper machine wet pressing trials were available for validation of the model predictions. In the pilot paper machine trials, the stock was a 40%/60% mixture of softwood and hardwood bleached pulp, slightly beaten to a Schopper-Riegler of 22.3 SR. The applied linear load in the shoe press was 600 kN/m and the machine speed was 600 m/min. The ingoing dryness was approximately 17%.

The dewatering efficiencies for the different grammages and felt configurations calculated by the model were compared using the obtained final dryness values. Since the pressure pulse applied in the model did not drop at the end of the pulse, no in-nip rewetting is included in the values. The same applied for the case of post-nip rewetting. The final dryness values were

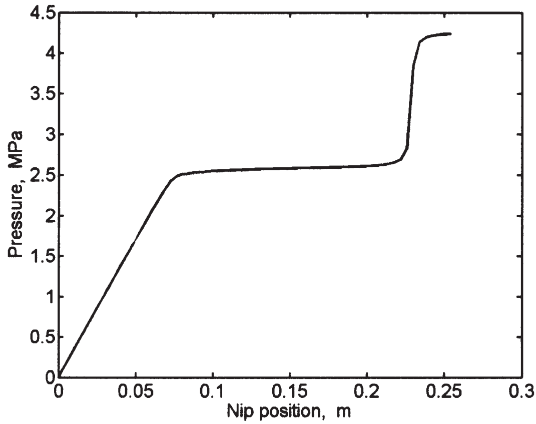


**Figure 7** The applied shoe press pulse for 600 kN/m linear load, 600 m/min machine speed and 254 mm nip length.

calculated from the initial dryness and the change in the model domain volume.

## RESULTS AND DISCUSSION

The model calculations revealed how the compaction of the web differed in different locations at the end of the applied press pulse. A plot of the local dryness also showed where the web was compacted (Figure 8). Right below the batt fibres was an area with high compaction. For low grammages, these areas reached all the way through the web to the roll. Between the batt fibres a lower compaction was observed. This lower compaction was more pronounced for the cases with a coarse model felt. Since the web was assumed fully saturated, the low compaction areas also corresponded to low dryness and vice versa. The dryness of the low compaction areas was lower for the cases with coarse batt fibres, which means that there was more water left close to surface.

In all cases there was a stratification, i.e. layers of increasing dryness, in the out-of-plane direction between the batt fibres. In the high grammage cases, stratification was also observed further into the web with a local maximum dryness just below the interaction layer. This stratified layer corresponded to a zone with a low permeability, which delayed the dewatering for high grammages and lead to lower final dryness values.

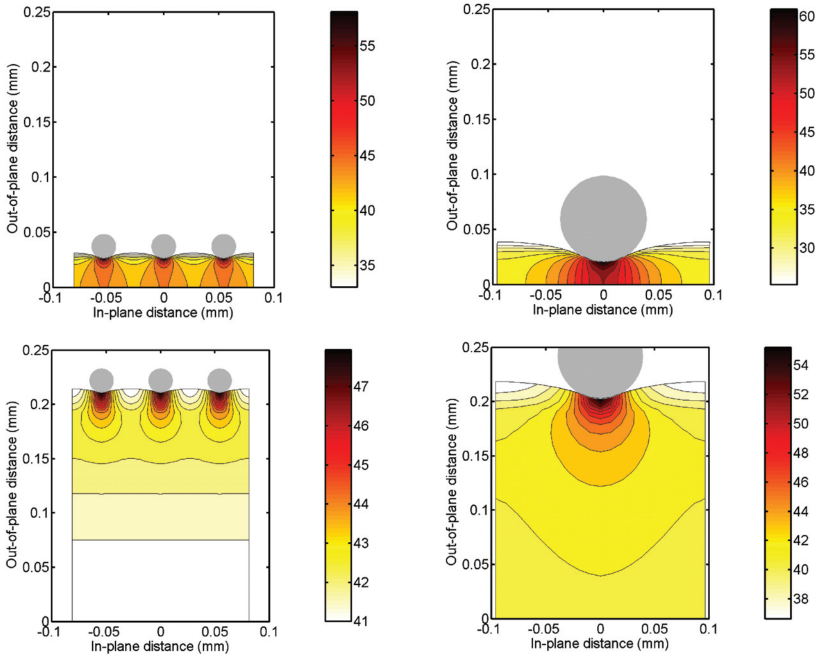


**Figure 8** Local dryness for a single-felted press nip calculated by the model for 22 μm (left) and 78 μm diameter batt fibres (right), and a grammage of 15 (upper) and 105 g/m$^2$ (lower).

For a double-felted press nip the difference in dewatering between the two batt fibre alignment configurations was large for low grammages, see Figure 9. Aligned batt fibres resulted in zones with high compaction between the two fibres. The compaction patterns resembled that of the single-felted press nip. The interspersed configuration on the other hand resulted in slightly lower compaction, but in a larger fraction of the web. This configuration would dewater efficiently for low grammages, if it were possible to adapt the properties of the upper felt with those of the lower felt in a real press nip.

In Figure 10, a single- and a double-felted press nip were compared for a wide range of grammages. For lower grammage webs, the single-felted configuration is more efficient in terms of dewatering, resulting in higher dryness values. This can be ascribed to the effect that only one interaction layer exists. At higher grammages, the dewatering drops for both configurations, which is caused by the local densification of the web in the vicinity of the felt surfaces.

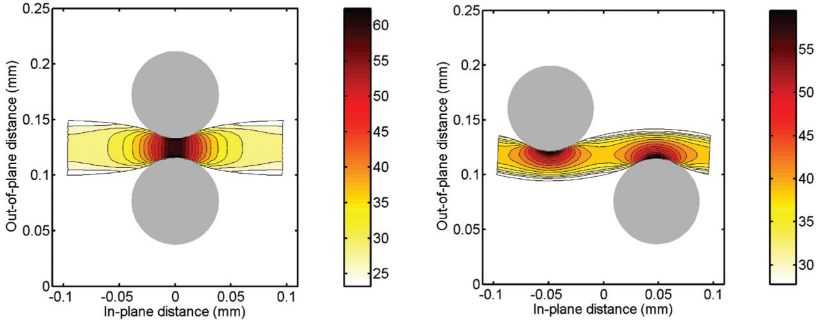


**Figure 9** Local dryness for a double-felted press nip calculated by the model for two different batt fibre configurations; aligned (left) and interspersed (right). (grammage 15 g/m$^2$, batt fibre diameter 78 µm).

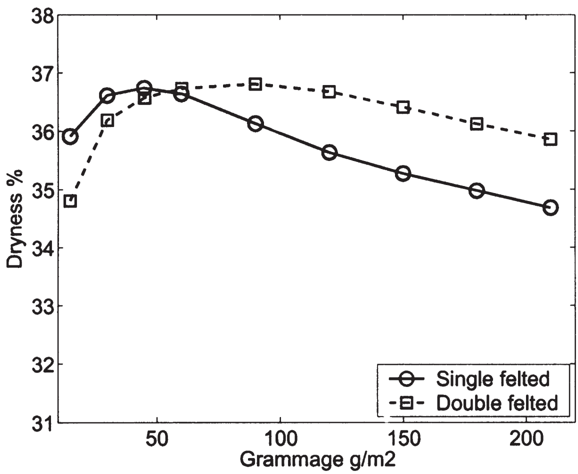


**Figure 10** Comparison of single- with double-felted press configuration for a shoe press nip, as a function of web grammages. (linear load 600 kN/m, machine speed 600 m/min, initial dryness 17%, batt fibre diameter 43 µm).

Here, the double-felted configuration is more efficient as the water is removed through two surfaces. At very high grammages there would be next to no dewatering at all and both curves would approach the initial dryness. For the single-felted nip it can be seen that the curve levelled off slightly, as was expected.

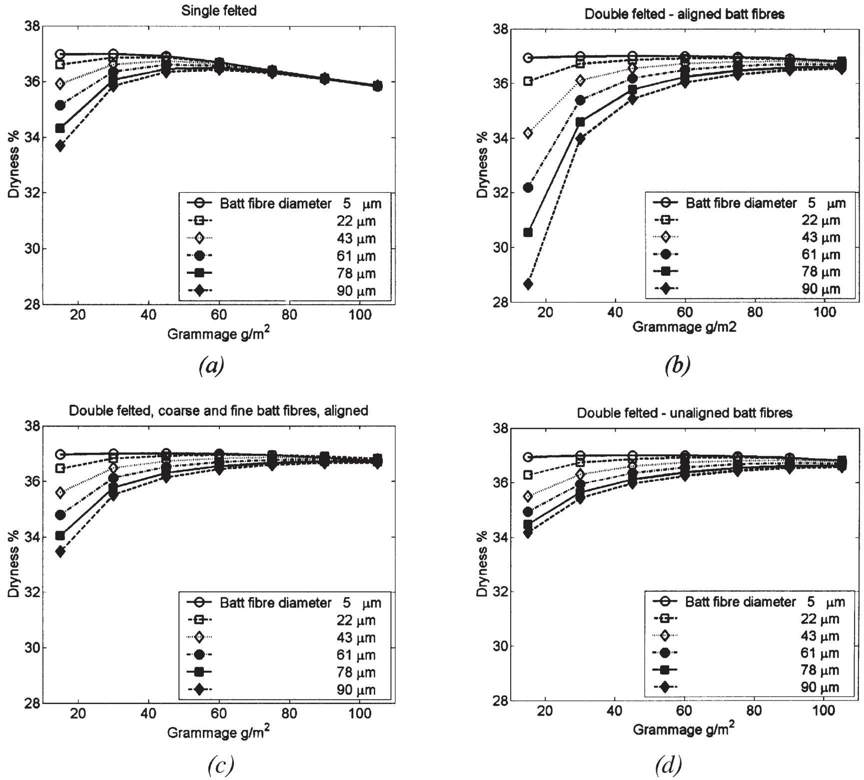


**Figure 11** Calculated dryness for different felt configurations (linear load 600 kN/m, machine speed 600 m/min, initial dryness 17%); (a) Single-felted, (b) Double-felted with identical and aligned batt fibres (c) Double-felted with two different felts: as in (c), but one felt has half batt fibre diameters and twice as many fibres (d) Double-felted with identical and interspersed batt fibres.

Figure 11 compares dewatering in a single-felted press nip with three configurations of double-felted press nips: two with batt fibres of identical size on both sides, in an aligned and an interspersed configuration, and one with batt fibres of half size on one side. The dewatering was calculated for grammages from 15 to 105 g/m$^2$, and for batt fibre diameters from 5 to 90 µm.

For the single-felted press nip (Figure 11 a) the differences between the felts were small for high grammages while they were large in the low grammage region. This behaviour was expected since for low grammages a coarse batt fibre leaves a larger part of the web with a lower dryness than a fine batt fibre with the same open felt area fraction. At higher grammages, felts with coarser batt fibres left larger open areas compared with a felt with fine batt fibres. Therefore one should expect a felt with coarse batt fibres to dewater better than a felt with fine batt fibres at high grammages. This difference in dewatering was also present in the calculation results for the single-felted case but, for the chosen simulation conditions, the differences were small and therefore not visible in Figure 11.

It was also apparent that each felt had an optimal grammage range: if the grammage was too low the felt left too many areas uncompressed; if the grammage was too high the open areas of the felt were too small for a sufficient water flow in the available time. The optimal grammage range shifted to lower grammages for finer batt fibres. For the 22 μm batt fibre, the optimal range was between 30 and 45 $g/m^2$ while it was between 45 and 60 $g/m^2$ for the 78 μm batt fibre in the single-felted press configuration, see Figure 11 (a).

For a double-felted press nip with equal felts on both sides and with an alignment of the batt fibres, the felts with fine batt fibre dewatered best at low grammages as in the single-felted cases, see Figure 11 (b). The dryness after the press nip was, however, more sensitive to the grammage for a given felt. For a completely symmetric model situation, with batt fibres aligned on each side of the web, the double-felted nip would correspond to a single felted nip with half the grammage. The values for the double-felted nip in the grammage range 30 to 105 $g/m^2$ corresponded quite well to that of the single-felted values in the range 15 to 50 $g/m^2$.

In a real double-felted press nip, batt fibre alignment is difficult to control. In this model it could however be prescribed. It was therefore of interest to study how the alignment affected the dewatering. In Figure 11 (d) calculation results from a double-felted press nip with equal felts and completely interspersed batt fibres are shown. The alignment was important for low grammages and coarse batt fibres. The felts with 90 μm batt fibres dewatered better in a double-felted press nip with interspersed fibres than in single-felted press nip.

It was also interesting to study how combinations of different felts in a double-felted press nip dewatered. In Figure 11 (c), the web was pressed in a nip with one felt with coarse batt fibres and one felt with fine batt fibres. In all cases, the batt fibres of the lower felt are half the sizes of those of the upper felt. For low grammages the calculated dewatering resembled the dewatering in a single-felted press nip with the coarser of felts. For high grammages the dewatering did not show the drop that is present for the single-felted nip, except for felts with very fine batt fibres. The conclusion from this is that the

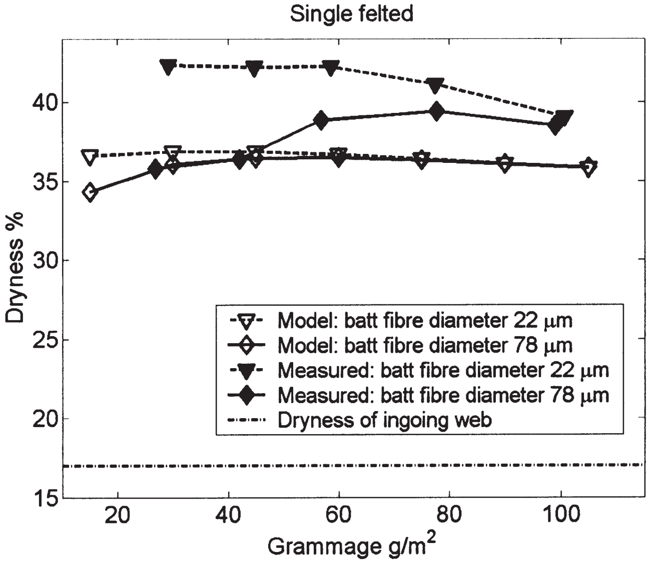


**Figure 12** Comparison of model calculations with measured values from the pilot paper machine EuroFEX.(linear load 600 kN/m, machine speed 600 m/min, initial dryness 17%, batt fibre diameter 43 μm).

combination of one coarse and one fine felt may be advantageous in terms of dewatering.

Dryness values calculated by the model were also compared with measured values from trials on STFI-Packforsk's pilot paper machine, EuroFEX (Figure 12). The experimental results have been published by Gullbrand [23]. The calculated and measured dryness curves have some features in common. For the felts with coarse batt fibres the achieved dryness drops at low grammages. This is not the case for the felts with fine batt fibres. At high grammages the achieved dryness for all felts drop. The felts with coarse batt fibres consequently have an optimal dewatering at a certain grammage. For the felts with fine batt fibres the measured values are several percent units higher than the calculated values. For the felts with coarse batt fibres the discrepancies are smaller. These discrepancies are not minor and were anticipated, since the model presented here is an approximation of the very complex behaviour of a real press nip. However, the model still captures the general behaviour of the dewatering in a press nip, especially the highly grammage dependent dewatering results, the fact that the achievable dryness for most felts is decreasing both for lower and higher grammages and the influence of the felt surface roughness.

## CONCLUSIONS

A numerical model of wet pressing has been presented that includes the effect of the uneven pressure application on the web by the batt fibres of the felt. The model was used to study several combinations of grammages and felt configurations for both single- and double-felted press nips. Qualitatively, the model behaved in the same way as would be expected based on experimental results. Results obtained with the model gave important insights into the physics of wet pressing. It could clearly be pointed out why different felt model surfaces and the combination of those dewatered differently for different grammages without performing expensive laboratory or pilot paper machine trials.

To become a more accurate quantitative tool the numerical model needs further improvements, e.g. a more realistic treatment of the felts surface topology, how it changes with the applied load or an exact description of the dynamic fibre network rheology. This research involves both experimental felt surface characterisation and modelling work. It may also be necessary to abandon the two-dimensional approach and develop a three-dimensional model with measured felt topologies as surface contact boundary conditions.

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## LITERATURE

1. Wrist, P.E., "The Present State of Our Knowledge of the Fundamentals of Wet Pressing", Pulp & Paper Magazine of Canada, 1964 (July), T284–T296.
2. Oliver, J.F. and Wiseman, N., "Water Removal in Wet Pressing: The Effect of Felt Roughness", Pulp and Paper of Canada, Trans. Tech. Sect., 1978, 79 (4), TR104–TR109.

3. Sze, D.H., "Measuring Wet Press Felt Pressure Uniformity and its Effects on Sheet Solids", Tappi Journal, 1986, 69 (4), 120–124.
4. McDonald, J.D. and Pikulik, I.I., "Felt Construction and Water Removal in a Press Nip", Tappi Engineering Conference, 1992, 869–876.
5. Fekete, E.Z. and Wiebe, K.M., "The Limits of Pressing", Tappi Journal, 1999, 82 (11), 81–87.
6. I'Anson, S. and Ashworth, T., "Differentiated-Permeability Surface Layer (DPSL) Pressing Theory", Tappi Journal, 2000 (November), 70.
7. Vomhoff, H. and Norman B., "Model Experiments of Wet Pressing – the Influence of Felt Surface Structure", Nordic Pulp and Paper Research Journal, 1997, 12 (1), 54–60.
8. Vomhoff, H., Martinez, D.M., and Norman, B., "The Transversal Steady-State Permeability of a Fibre Web Compressed Between Rough Permeable Surfaces", Journal of Pulp and Paper Science, 2000, 26 (12), 428–436
9. El-Hosseiny, F., "Mathematical modeling of wet pressing of paper", Nord. Pulp Pap. Res. J. 6: 1, 30–34, (1991).
10. Kerekes R. J., McDonald J. D., "A Decreasing Permeability Model of Wet Pressing", 76th Annual CPPA meeting, Preprints 'B', pp 173–179, Montreal, (1990).
11. Kerekes R. J., McDonald J. D., "A Decreasing Permeability Model of Wet Pressing: Theory", TAPPI eng. conf., book 2, pp 551–558, Nashville, (1991).
12. McDonald J. D., Kerekes R. J., "A Decreasing Permeability Model of Wet Pressing: Applications", TAPPI eng. conf., book 2, pp 559–568, Nashville, (1991).
13. McDonald J. D., Kerekes R. J., "A Decreasing Permeability Model of Wet Pressing: with Rewetting", TAPPI eng. conf., book 1, pp 109–116, San Francisco, (1994).
14. Kataja, M., Hiltunen, K., Talja R., Timonen, J., "A Hydrodynamical Model of Wet Pressing of Paper", TAPPI Eng. Conf., Boston, Sep. 14–17 1992, 403–424, (1992).
15. Kataja, M., Hiltunen, K., Timonen, J., "Flow of water and air in a compressible porous medium. A model of wet pressing of paper", J. Phys. D: Appl. Phys. 25(1992) 1053–1063, (1992).
16. Bloch, J.-F., "Transferts de Masse et de Chaleur dans les Milieux Poreux Deformables non Satures: Application au Pressage du Papier", Ph.D. thesis, Institut National Polytechnique de Grenoble, Grenoble, (1995).
17. Bloch, J.-F., Silvy, J., Roux, J.-C., Aurialt, J.-L., "Wet pressing of paper and filtration laws", Recueil de Conférences, 7th World Filtration Congress, Budapest, vol I, 47–51, (1996).
18. Riepen, M., "An Inside View on Impulse Drying Phenomena by Modelling", Tappi J. 83:10, (2000).
19. Gustafsson, J-E., Lobosco, V., Kaul, V., "Densification and Dewatering in High Temperature Wet Pressing", XIIth Fundamental Research Symposium, Oxford, UK., Vol. 1, 149–155, (2001).
20. Andersson B. "Beräkning av effekten av ojämnheter i pressfiltar vid våtpressning av papper", Master Thesis, Royal Institute of Technology, Department of Signals Sensors & Systems, IR-RT-EX-0107, (2001).

21. CHAU P., "Modelling of the non-uniform compression of a fibre network in wet pressing", Master Thesis, Royal Institute of Technology, Department of Solid Mechanics, (2003).
22. ABAQUS/Standard, "User's Manual", Hibbitt, Karlsson & Sorensen, Inc., Pawtucket, USA.
23. GULLBRAND, J., "The influence of stress variations in wet pressing", Licentiate Thesis, Royal Institute of Technology, Department of Fibre and Polymer Technology, Stockholm, (2004).
24. LOBOSCO, V., KAUL, V., "An elastic/viscoplastic model of the fibre network stress in wet pressing: Part I", Nord. Pulp Pap. Res. J., 16(1): 12–17, (2001).
25. LOBOSCO, V., KAUL, V., "An elastic/viscoplastic model of the fibre network stress in wet pressing: Part 2 Accounting for pulp properties and web temperature", Nord. Pulp Pap. Res. J., 16(4): 313–318, (2001).
26. VOMHOFF, H.: Studies of the Dynamic Compressibility of Water-saturated Fibre Networks, Tappi Journal, 2001, 84 (4), 72–75.
27. LAIVINS, G.V., SCALLAN, A.M., "Removal of Water from Pulps by Pressing, Part I: Inter- and Intra-wall Water", TAPPI Engineering Conf., (1993).
28. VOMHOFF, H., "On the in-plane permeability of water-saturated fibre webs", Nordic Pulp and Paper Research Journal, 2000, 15 (3), 200–204.

**Transcription of Discussion**

# MODELLING OF MECHANICAL DEWATERING IN CONTACT WITH ROUGH PERMEABLE SURFACES

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Some years ago, I did some similar studies to yours, and got similar experimental results. I got press felts of different weave designs from a felt supplier. I did report my results at some conferences, like TAPPI's, but I don't think they caused any interest in the industry.

The effects of the varying felt structure design on water removal was very pronounced at low basis weights of the paper, as also shown in your experiments. The reason is, as you mention, the uneven pressure exerted by the batt strands on the very thin paper.

What I then did was to put a very thin (1 *mm*), very flexible rubber blanket on top of the solid press roll, and passed the moist paper through the nip resting on this blanket. The rubber blanket will flex locally dependent on the surface topography of the felt, thus causing a much more uniform pressure on the paper. I got a very pronounced rise in the solids content of the web after the nip.

I assume it may be difficult to implement the use of the thin flexible rubber blanket under the sheet in the nip but I think it would be worthwhile to try it.

*Jan-Erik Gustafsson*

Interesting comment. You could imagine that you mirror the felt in the rubber perhaps, and in that way you go towards the interspersed configuration in some way. I suppose this could also be calculated by the model by introducing a flexible layer between the paper and the roll.

*David McDonald* Paprican

Your model takes into account the uniformity of pressure application but in comparison how large do you estimate the effect of in-nip rewetting to be, when the felt and the paper begin to separate?

*Jan-Erik Gustafsson*

This model does not consider the rewetting at all, for two reasons. The expansion part of the press nip is not included in the model, because the model cannot calculate the plastic deformation which we know we have in the paper web. The other reason is that there is no modelling of the splitting between the paper and the felt.

*David McDonald*

That is why I am wondering about it. There might be an alternate explanation for your trends. Could you show the slide that has the different batt fibre diameters in contact with the paper (see for example figure 3)? When you look at that slide, you expect that water fills the gap between the batt fibres roughly to their depth. So that with batt fibres of 22 $\mu m$ you would have a 22 $\mu m$ reservoir of water sitting in contact with the sheet and with the large batt fibres you would have 78 $\mu m$. When the two separate, the capillary forces will tend to pull the water towards the paper and 1 $\mu m$ of water is roughly equal to 1 $g\ m^{-2}$, so you are talking about a relatively large amount of water that could be transferred in that splitting. With a higher grammage, the amount of water transferred is not going to be important in the relative sense, but with the lower grammage, you can see the felts give different paper solids. That could be caused by the water at the surface being transferred during the splitting. Could you comment on the relative magnitude of the in-nip splitting of the water layer compared to the phenomena you discuss?

*Jan-Erik Gustafsson*

My comment is that in this area between the batt fibres and the felt, there is of course water and the question is where would this water go when the felt and the paper are separated. I would expect that it has a higher tendency to go towards the paper, but this cannot be predicted by the model and it is not included in the model.

*Anders Åström*

One final question. When you looked at this model, there is one type of fibre and one type of paper, but how will the stiffness of the web affect the compression and is, for example, the optimal de-watering versus grammage affected?

*Jan-Erik Gustafsson*

The material properties are included in model. To try another material, another type of paper, we will have to retune this of course as well as the permeability. I don't want to speculate which way the curves would shift if we did that.