

The role of evaporative dewatering in impulse pressing

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ABSTRACT: The objective was to link heat transfer to water removal mechanisms, specifically evaporative dewatering, in impulse pressing experiments. Two independent laboratory devices—a platen press and a shoe press—were used to impulse press fiber webs made from softwood bleached kraft (SBK) over a range of basis weights (20–200 g/m²). In the platen press experiments, evaporative dewatering was evaluated by comparing the measured heat input to the amount of heat theoretically required to vaporize the water in excess of unheated wet pressing. Evaporative dewatering was found to be most pronounced for lightweight sheets, and enhanced dewatering can be attributed to this mechanism and other high-temperature mechanisms for basis weights above 60 g/m². In the shoe press experiments, a composite sheet of five 30-g/m² webs was used to evaluate profiles for resulting dryness, density, and water retention value (WRV) in the thickness direction. Evaporative effects were confined principally to the layer directly in contact with the heated surface.

Application: A better understanding of the water removal mechanisms in impulse pressing process may accelerate the industrial application of impulse technology.

From its conception over two decades ago [1] until today, impulse drying has received a great deal of attention from various research groups. In short, impulse drying combines an extended nip press with a roll heated to temperatures well above 100°C [1]. The combination of high mechanical load and high temperature creates a dramatic increase in solids content, translating into a potential for energy savings and/or increased productivity [2]. At the same time, physical properties like strength and roll-side surface roughness can be improved [3]. However, sheet quality may deteriorate as a result of delamination, which arises when water flashes to steam during nip decompression. (A review article by van Lieshout [4] offers further information on impulse drying.)

Impulse drying, which is also called “impulse pressing,” has been studied in a number of contexts: laboratory-scale experiments [5–13], pilot plant trials [3, 14–17], and numerical simulations [18–20]. Despite these efforts, a full description of the underlying physical mechanisms remains incomplete. Enhanced dewatering can be attributed to the following effects: (a) displacement dewatering due to steam formation, (b) increased hydraulic pressure gradient via steam generation, (c) thermal softening of the fiber network, (d) reduced viscosity, and (e) evaporation. Separating these effects from one another is extremely challenging, given the limitations of experimental measurement techniques and modeling uncertainties.

There are some inadequately explored aspects of dewatering, however, that may help to clarify some of these mechanisms. For example, dewatering can be systematically studied as a function of basis weight so that water removal can be related to heat transfer. At relatively high basis weights, it is also possible to obtain approximate information regarding thickness-direction gradients by using multiply or composite sheets. In contrast to the work of Burton *et al.* [21], who measured the development of density gradients inside the nip, composite sheet studies allow us to estimate both moisture profiles after pressing and density profiles after drying. Tests with composite sheets also enable us to construct profiles for the water retention value (WRV), which may offer further clues as to the nature of the water removal processes in impulse pressing.

Our objective was to link heat transfer to dewatering, specifically evaporative losses, in impulse pressing experiments. We used two independent laboratory devices—a platen press and a shoe press—to impulse press fiber webs made from softwood bleached kraft (SBK) pulp over a range of basis weights ($w = 20\text{--}200$ g/m²). Qualitative trends regarding thickness-direction gradients were also of interest. To explore these trends, we carried out shoe press experiments with composite sheets formed from individual thin fiber webs.

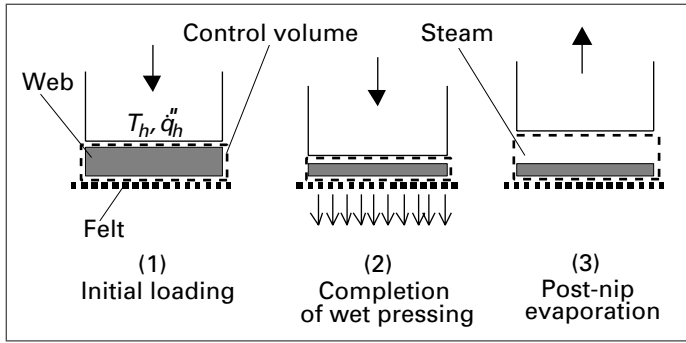
BACKGROUND

To evaluate the possible water removal mechanisms in impulse pressing, it is instructive to consider a general energy balance of the process. As shown in Fig. 1, the heated surface with temperature T_b supplies heat to the web while it is inside the nip. Part of this heat serves to raise the total enthalpy of the web (fibers, water, air, and possibly steam), while a portion of this energy is lost to the felt by conduction and convection. When the nip opens, the hot, wet web releases energy via flashing, thus supplying additional drying potential.

Some assumptions need to be made at this point in order to quantify the process. If steam-assisted displacement and other enhanced in-nip dewatering processes are ignored, the total water removal is simply due to unheated wet pressing accompanied by evaporation. Energy balances can be considered for two processes:

1. Sensible heating of the web inside the nip, combined with wet pressing (no additional dewatering via steam displacement or other high-temperature mechanisms) (1–2 in Fig. 1).
2. Evaporation with no heat transfer to the surroundings (2–3 in Fig. 1).

The control volume is defined as the web plus any evaporated steam, and if thickness-direction gradients and the contribution of air are ignored, the total change in enthalpy $\Delta b_{1,3}$, in kJ/m², is



1. Idealized in-nip dewatering and post-nip evaporation in impulse pressing.

PARAMETER	VALUE	ESTIMATED UNCERTAINTY
Basis weight, g/m ²	20-200	± 5%
Nip residence time, ms		
Platen press	25	± 3 ms
Shoe press	12	± 2 ms
Peak nip pressure, MPa		
Platen press	7.5	± 0.5 MPa
Shoe press	6.5	± 0.5 MPa
Platen/band temp., °C		
Platen press	25-300	± 2°C
Shoe press	25-300	± 4°C

1. Range of experimental parameters and associated uncertainty.

$$\Delta h_{1-3}'' = w \left[\underbrace{(h_{f,3} - h_{f,1}) + (MR_2 h_{w,2} - MR_1 h_{w,1})}_{(a)} + \underbrace{h_v (MR_2 - MR_3)}_{(b)} \right] \quad (1)$$

where h_f is the enthalpy of the fibers, h_w is the enthalpy of water, h_v is the heat of vaporization, and MR is the moisture ratio at a given state. Term (a) represents the change in sensible heat, while Term (b) represents the change in latent heat. If Δb_{1-3} is proportional to q_b'' , the energy supplied by the heated surface, Eq. 1 suggests that

$$q_h'' \propto a \Delta h_{th, sen}'' + b \Delta h_{th, lat}'' \quad (2)$$

In this expression, $\Delta b_{th, sen}''$ is the theoretical change in sensible heat, and $\Delta b_{th, lat}''$ is the theoretical change in latent heat, defined as

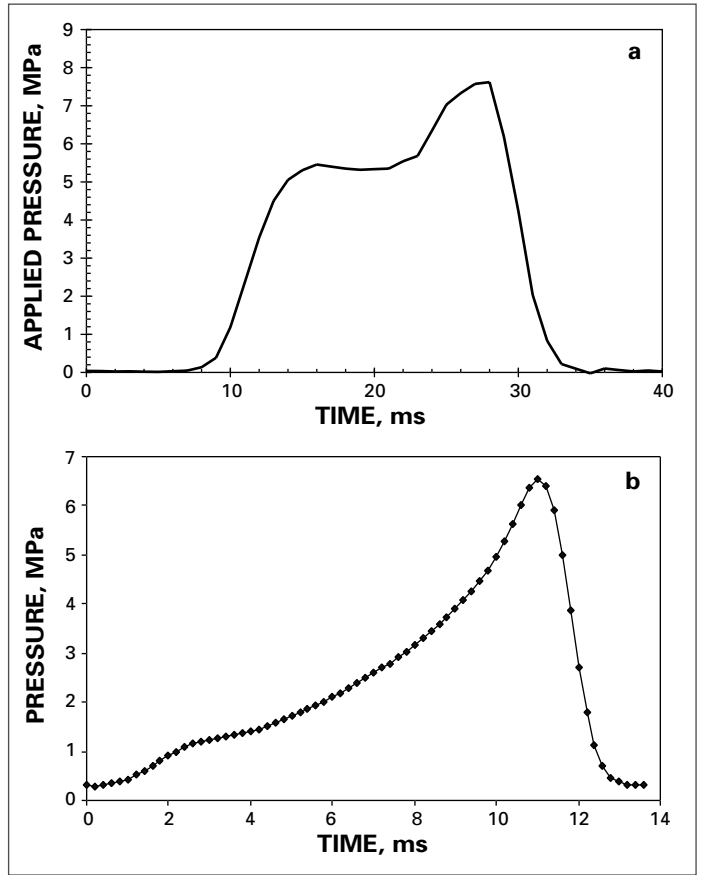
$$\Delta h_{th, lat}'' = w h_v (MR_2 - MR_3) \quad (3)$$

According to this line of reasoning, any dewatering in addition to the wet pressing contribution is completely embodied in $\Delta b_{th, lat}''$. A plot of q_b'' vs. $\Delta b_{th, lat}''$ thus gives an indication of the importance of evaporative dewatering. Two different regimes may be identified via slope b :

- $b \geq 1$ Felt heat losses and/or evaporative dewatering are important.
- $b < 1$ Evaporative dewatering and other mechanisms are important.

EXPERIMENTAL PROCEDURES

A bleached softwood kraft pulp refined to 25°SR was used as the furnish in all experiments. Handsheets with basis weights ranging from 20 g/m² to 200 g/m² were produced with a Finnish former in accordance with ISO 5269/1-1979. The solids content



2. Typical nip pressure profiles in (a) platen press and (b) shoe press equipment. (Part b obtained from Nilsson [10].)

was approximately 30% after forming and light pressing. For the platen press experiments, four samples 80 mm in diameter were punched out of each sheet (160 mm by 160 mm), while the entire sheet was used in the shoe press experiments.

The platen press is equipped with a load cell, a heated steel block, and a control system. An ultra-thin, fast-response thermocouple allows for the concurrent measurement of T_b and the instantaneous heat flux, q'' [22]. The total energy supplied is computed from

$$q_h'' = \int_{\Delta t} q'' dt \quad (4)$$

where Δt is the nip residence time and q'' was calculated from surface temperature data according to the numerical procedure presented by Taler [23].

We also used a shoe press developed by the Dept. of Pulp and Paper Chemistry and Technology at the Royal Institute of Technology (KTH) in Stockholm. The KTH Shoe Press features a heated metal band that is passed through the nip formed between a roll that is 300 mm in diameter and 200 mm wide and a concave shoe that is 42 mm long. The web, felt, and a lubricated plastic sheet follow the band. In these experiments, the steel band was sufficiently thick (0.5 mm) that its thermal performance was fairly close to that of a more massive heated roll [10]. Commercial fine paper press felts were used in all tests.

Figure 2 shows typical pressure profiles from both pieces of equipment. Table I summarizes the operating parameters and their uncertainty ranges.

Each trial was relatively straightforward. The sample was first weighed, pressed at a given temperature, and weighed directly after pressing and oven drying (10 min at 110°C). At least three independent trials were performed for the platen press

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experiments for the given process conditions, while two trials were performed for each of the shoe press experiments. Separate experiments were also conducted in order for us to qualitatively assess thickness-direction profiles and to have our tests resemble the tests conducted by Wicks [24] for wet pressing.

In our study, five 30-g/m² sheets were stacked together to form a composite web. After pressing, each layer was carefully removed, placed in a plastic bag, and subsequently analyzed. The five layers obtained from one test were weighed in order to construct moisture profiles, while water retention value (WRV) measurements were performed in a separate test under identical processing conditions. The WRV is defined as

$$\text{WRV} = \frac{m_w}{m_{bd}} \quad (5)$$

and was determined according to SCAN-C 63:00. In this method, the wet sample is centrifuged at 3000 g for 15 min, and the mass of water after centrifuging (m_w) and the bone-dry mass (m_{bd}) are determined gravimetrically. A slight deviation from the method's procedure was necessary: since the samples had a low mass, each sample was wetted before centrifuging. Early trials with dyed fibers in every other sheet in the stack revealed virtually no fiber carryover between individual layers, which demonstrated the suitability of this method.

The sheet caliper l for each layer after drying was measured by SCAN-P 141X in a series of early trials with relatively wet webs (25% initial solids content). The sheet density ρ_p was computed from

$$\rho_p = \frac{w}{l} \quad (6)$$

RESULTS

Dewatering performance

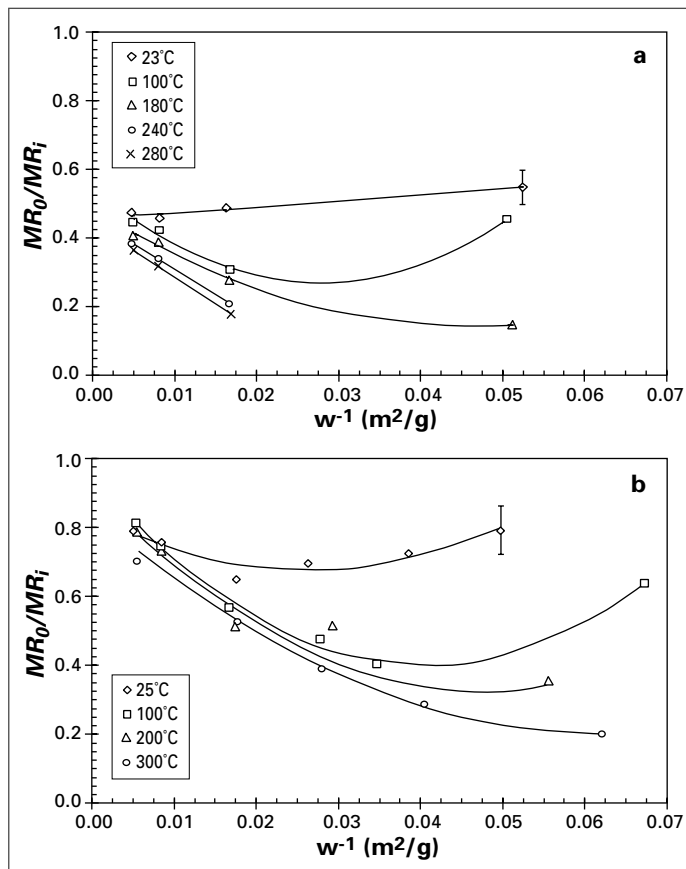
Results from both platen and shoe press experiments are presented as modified Sweet-Wahlström diagrams in Fig. 3. In these diagrams, the final moisture ratio MR_o was normalized by the initial moisture ratio MR_i in order to eliminate some of the data scatter produced by slight variations in MR_i . Data points represent the average of two or more experiments at a given basis weight and temperature, and error bars indicate the approximate uncertainty in the measurements.

As the figure shows, overall dewatering performance is better with the platen press, as a result of the longer nip residence time. For the unheated platen press experiments, the constant positive slope indicates that the process is controlled by compression across the range of w^{-1} , the inverse of basis weights tested. Nip rewet R may be estimated by Eq. 7 [25, 26]:

$$MR_o = MR_m + \frac{R}{w} \quad (7)$$

where MR_m is the mid-nip moisture ratio, with $MR_i = 2.33$, $MR_m = 1.06$, and $R = 4.1$ g/m².

Unheated shoe press experiments, in contrast, show behavior more typical of commercial units—i.e., a compression-controlled region at high w^{-1} and a flow-controlled region at low w^{-1} . A minimum in MR_o/MR_i appears at a basis weight of about 60 g/m². In this case, $MR_m = 1.35$ and $R = 9.7$ g/m², which are in line with previously reported values [27].



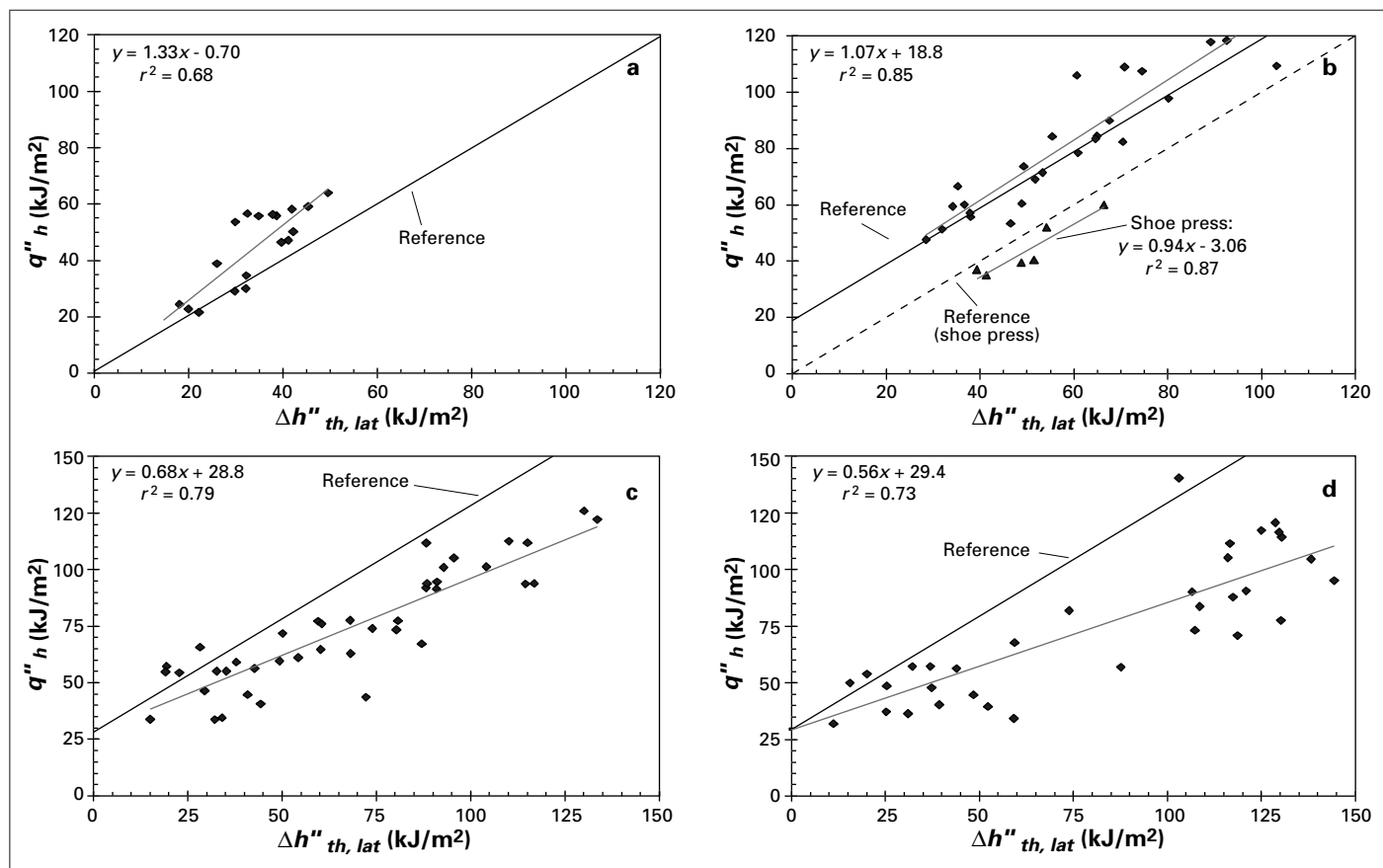
3. Normalized final moisture ratio after pressing vs. inverse basis weight for (a) platen press and (b) shoe press experiments. (Each series has been fitted with a polynomial curve to illustrate trends.)

The addition of heat changes the situation dramatically in both experiments. For basis weights under 40 g/m², evaporative dewatering counterbalances nip rewet, changing the shape of the curves as the hot surface temperature is raised. Differences are more modest for higher basis weights, and a water removal limit is reached for the shoe press experiments with $w > 120$ g/m² and $T_b > 300^\circ\text{C}$. Boerner and Orloff [6] observed a similar trend, although a dewatering limit was reached at a higher basis weight (400 g/m²) in their experiments. The relatively large scatter in the shoe press experimental data for $T_b = 200^\circ\text{C}$ is most likely attributable to unforeseen variations in process parameters (most probably nip pressure profile).

Aside from dewatering performance, delamination was observed in some of the experiments. This tendency was most clearly seen in the platen press trials with heavy sheets, even at modest temperatures (200°C and above). Runnability problems arose with the platen press experiments for the sheets of low basis weight because the felt was adhering to the heated platen when $T_b > 180^\circ\text{C}$ (hence the missing data in Fig. 3). No attempt was made to further characterize delamination or to evaluate changes in strength properties.

Evaluation of evaporative dewatering

The total heat transfer from the platen was found to be fairly independent of basis weight, which makes it appropriate to use Eq. 2 in studying evaporative effects. The relationship between q_b'' and $\Delta b''_{b,lat}$ is illustrated in Fig. 4. A straight line is fitted to the



4. Energy supplied vs. theoretical energy in the platen press experiments. Basis weights were: (a) 20 g/m², (b) 60 g/m², (c) 120 g/m², and (d) 200 g/m². The shoe press results included in graph (b) were obtained from Nilsson [10].

data in each case, and a reference line with a slope of one is drawn from the common y -intercept for comparison.

For the given process conditions, it appears that evaporative dewatering and/or felt heat losses dominate for basis weight $w \leq 60$ g/m². Graph B, with $w = 60$ g/m², includes shoe press data obtained in an independent study [10] and indicates that the platen press and shoe press have similar performance. At higher basis weights, b drops well below 1, suggesting that other mechanisms contribute in part to the enhanced dewatering. Sensible heating effects are reflected in the y -intercept values, which rise with an increase in basis weight (Eq. 1).

With these results, it is possible to estimate the relative importance of dewatering via paths other than evaporation for the high-basis-weight data ($w \geq 120$ g/m²). If the felt heat losses are negligible, slope b from Eq. 2 may be rewritten as

$$b = \frac{\Delta MR_{evap}}{\Delta MR_{tot} - \Delta MR_{ref}} \quad (8)$$

where ΔMR_{evap} is the change in the moisture ratio due to evaporation, ΔMR_{tot} is the change in the total moisture ratio, and ΔMR_{ref} is the change in the moisture

ratio for the reference (unheated wet pressing). An impulse pressing efficiency, ϵ_{imp} , may be defined as

$$\epsilon_{imp} = \frac{\Delta MR_{tot} - \Delta MR_{ref} - \Delta MR_{evap}}{\Delta MR_{evap}} = \frac{1 - b}{b} \quad (9)$$

This variable represents the ratio of non-evaporative enhanced dewatering to evaporative dewatering. For $w = 120$ g/m², $\epsilon_{imp} = 0.47$, which suggests that evaporative dewatering and other mechanisms have a similar effect. At a higher basis weight (200 g/m²), $\epsilon_{imp} = 0.78$, indicating that most of the enhanced dewatering in this case is largely due to mechanisms other than evaporation.

Thickness-direction gradients

Composite sheet experiments were performed with the shoe press in order that we might observe trends in thickness-direction properties. These findings are summarized in Fig. 5, which shows water retention values for each layer as a function of dryness. A reference curve was obtained from wet pressing experiments in which the composite sheet was pressed one, two, or four times in succession. Most of the subsequent data fall on this curve, with the exception of the layers adjacent to the heated band. Next to

the band, elevated temperatures cause a departure from the expected relationship between WRV and dryness.

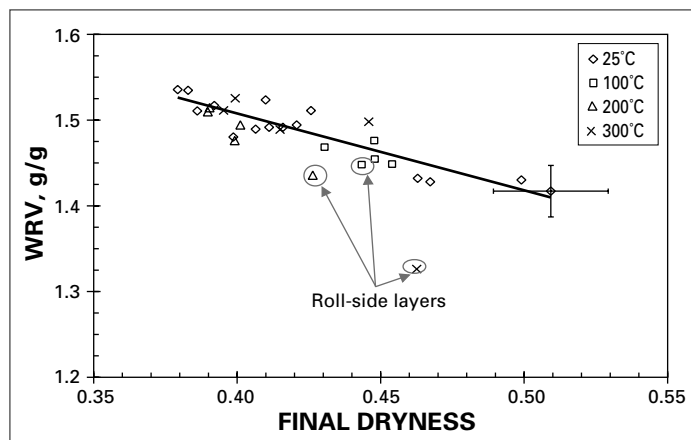
Figure 5 also reveals that, with $T_b > 100^\circ\text{C}$, the roll-side layer reached a higher dryness than the other layers reached. This result is seen more clearly for $T_b = 200^\circ\text{C}$ and $T_b = 300^\circ\text{C}$ in Fig. 6, which illustrates the variation of WRV in the thickness direction for the different temperatures.

Density profiles from the early trials are shown in Fig. 7. Although the statistical significance of the data is relatively weak, there seems to be slight densification towards the felt side, which is in accordance with results presented by Wicks [24]. Density values of the roll-side sheets are somewhat higher than the densities for the unheated reference for temperatures above 100°C .

DISCUSSION

It is not surprising that evaporative effects are more apparent for lighter sheets. However, the fact that other mechanisms are at play at higher basis weights is intriguing. Some researchers have concluded that dewatering in impulse pressing is characterized mainly by hot pressing and evaporation, with no contribution from an in-nip phase

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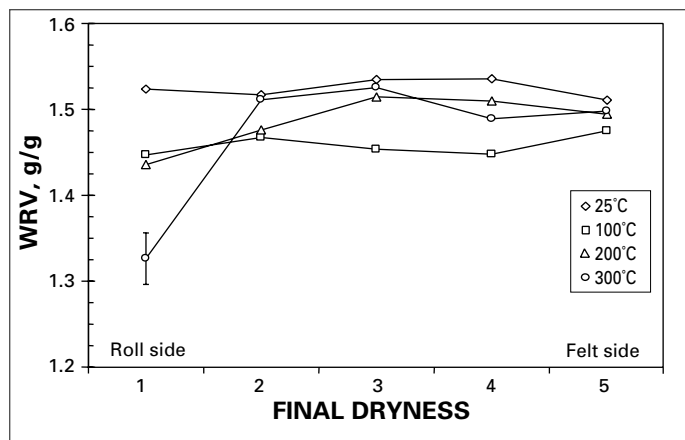
5. Water retention value vs. outgoing dryness for each layer within a 150-g/m² composite sheet in the shoe press experiments.

change [28–29]. Hot pressing effects such as reduced viscosity and web compressibility may play a role, but they should have diminishing effects at higher basis weights, owing to the sharp temperature gradients within the web. Steam-assisted displacement dewatering may be a key factor here, at least for the experiments considered in this study. Results from numerical modeling [19–20] point to in-nip steam displacement as a potential source of dewatering.

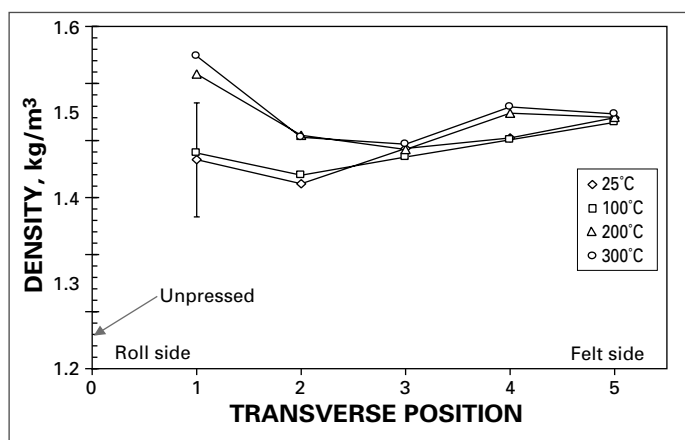
Since enhanced dewatering was found to depend upon basis weight in this study, it is possible that steam-assisted displacement dewatering takes place; however, it occurs primarily as a result of a phase change during nip decompression and not as a result of processes occurring at mid-nip. This phenomenon—termed ‘flashing-assisted displacement dewatering’ [8]—cannot be observed at lower basis weights for two reasons. First, heat losses to the felt are high here, so the flashing potential is relatively low. Second, evaporative effects dominate, as explained. An increase in the hydraulic pressure gradient may also be important, but it is not possible to evaluate its role from these results. Recent numerical simulations [18] have demonstrated that this mechanism may be crucial if the roll-side hydraulic pressure levels are sufficiently low inside the nip.

The nature of the water removal mechanisms has a number of important consequences. From an energy point of view, evaporative dewatering resulting from impulse pressing is less desirable than displacement dewatering, since low-cost steam in the dryer section could just as well be used to vaporize water from the web. Our findings show that lightweight sheets are most susceptible to evaporative effects, so extra attention may be required for these grades. In addition, the existence of flashing-assisted displacement dewatering suggests that the nip pressure profile can be modified to optimize water removal [8], possibly in combination with a delamination control scheme as presented by Orloff *et al.* [30]. Of course it is not certain that the findings of our study hold true under industrial conditions, but they do indicate possible trends.

With regard to the thickness-direction profiles, additional hornification is shown for the uppermost layer in direct contact with the heated surface. Unfortunately, the experimental uncertainty makes it difficult to attain a definitive conclusion on the processes that generate a deviation from the density–WRV rela-



6. WRV profile for the five layers within a 150-g/m² composite sheet in the shoe press experiments.



7. Thickness-direction density profile for a 150-g/m² composite sheet in early shoe press experiments (initial dryness 25%).

tionship at elevated temperatures. Several mechanisms could be active simultaneously and could cause or contribute to both densification and hornification. In fact, both wet pressing and evaporative drying cause hornification, and data on WRV vs. dryness typically fall on a single curve if the conditions for water removal are the same [31]. Hornification may be enhanced at higher temperatures [31], so our findings may simply reflect the sharp temperature gradients in the thickness direction. Another possibility is that evaporation, which is highest in the layers closest to the heated surface, leads to a reduction in WRV.

Computational studies [32] demonstrated the possible existence of steep moisture profiles during a flash drying process. In addition, the observed densification of the upper-layer sheets for high temperature conditions may be caused by impulse pressing mechanisms. Such a tendency has been reported previously for in-nip measurements [21], but densification was not seen in microscopic cross-section images of freeze-dried webs obtained from pilot-scale impulse pressing trials [14]. It is possible that this finding is an artifact of the measurement technique: a reduction in surface roughness on the roll side could cause an underprediction in the measured sheet caliper, hence overestimating ρ_p for the uppermost sheet.

CONCLUDING REMARKS

Both platen press and shoe press experiments in impulse pressing show that water removal increases with temperature and that elevated temperatures have the greatest impact on grades of low basis weight. In the platen press experiments, enhanced dewatering via evaporative dewatering dominates for basis weights less than or equal to 60 g/m², while other mechanisms accounted for up to 80% of the additional water removal for heavier sheets. Both displacement dewatering (most probably flashing-assisted) and increased hydraulic pressure gradients are likely candidates in this case.

Under impulse pressing conditions, the water retention value relates well to the final dryness of each layer in the composite sheet experiments, except for the uppermost sheets. For the uppermost sheets, the lower WRV is attributed to high local temperatures and/or evaporative effects. For future studies, we would like to see if our findings hold true for different process conditions, specifically shorter nip residence times and higher initial dryness levels. Impulse pressing is a fascinating area of papermaking research, and it is hoped that studies of this kind will soon transform this research into reality. TJ

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NOMENCLATURE

a, b	coefficients
h_f, h_w	fiber, water enthalpy, kJ/kg
h_v	latent heat of vaporization, kJ/kg
l	caliper, m
m_{bd}, m_w	bone-dry, water mass, kg
MR	moisture ratio
$\dot{q}''$	heat flux, kW/m ²
q_b''	supplied energy, kJ/m ²
R	rewet, g/m ²
SBK	softwood bleached kraft
T_b	surface temperature, °C
w	basis weight, g/m ²
WRV	water retention value
$\Delta h''$	enthalpy difference, kJ/m ²
Δt	nip residence time, ms
ϵ_{imp}	impulse pressing efficiency
ρ_p	sheet density, kg/m ³

Subscripts:

$evap, ref, tot$	evaporated, reference, total
i, o	initial, final
m	midnip
th, lat	theoretical, latent
th, sen	theoretical, sensible

INSIGHTS FROM THE AUTHORS

Impulse technology is one of the major research areas at STFI, The Swedish Pulp and Paper Research Institute. One aspect of this research pertains to the fundamental character of the physics of impulse technology. The role of evaporation as a dewatering mechanism is an issue that has been debated at length because it is so fundamental to the energy efficiency of the process.

Although the experimental work was rather time-consuming, it was both surprising and rewarding to find that our results agreed well with a previous study of ours [Nordic Pulp Paper Res. J. 16(4): 355(2001)]. In that study we argued that flashing-assisted displacement dewatering could appear as an impulse effect for high-grammage papers but not for thin ones.

This work brings us a step further towards understanding the physics of impulse drying. The next problem is to learn how to prevent delamination, which is connected to the flashing of water to steam at the unloading of the impulse nip. Mills will benefit from all

of the research being done on impulse drying if the process becomes commercial in the future.

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Lucisano



Petrini



Martin