Dynamic thickness and temperature measurements during wet pressing and impulse drying

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ABSTRACT: This paper summarizes the results of dynamic sheet thickness and temperature measurements during wet pressing or impulse drying on an electrohydraulic platen press. We based the dynamic thickness measurement system on the impedance variation caused by eddy currents induced by thin copper perforated targets that were embedded in the sheet. Temperature profiles were measured by embedded thermocouples.

Our main findings from this work are as follows:

- Impulse drying at elevated temperatures results in higher and nonuniform sheet compression as compared with wet pressing.
- Analysis of compression rate curves for both wet pressing and impulse drying indicate four compression intervals associated primarily with expression of air, expression of free water, expression of bound water, and rewet, respectively.
- The temperature profile in the sheet shows that a heat pipe process during prolonged decompression tends to even out the sheet temperature across the sheet and reduce the likelihood of sheet delamination.

Application: This study is a further step in the development of impulse drying. Understanding the physics of delamination and its prevention in the press nip also may help mills reduce delamination in the dryer section.

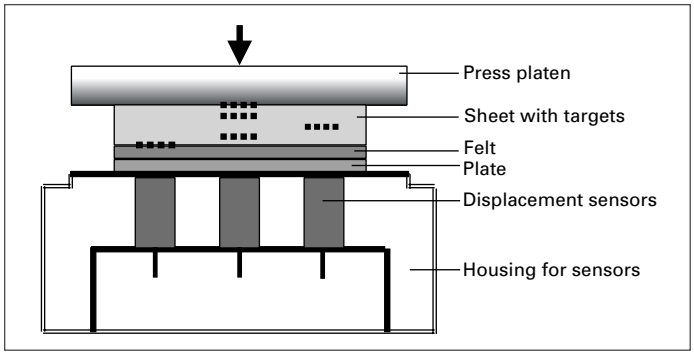
When designing the press section of a paper machine, machine builders try to maximize water removal. Estimates indicate that the energy expenditure for removing water by drying is reduced by 4% for every 1% gain in dryness in the press section. Preheating and/or impulse drying may increase sheet temperature and water removal in the press section.

A significant factor impeding implementation of impulse drying of linerboard and other heavy grades is delamination. A number of solutions have been suggested to inhibit delamination (Orloff [1], Orloff, et al. [2]). The main thrust was to reduce the imbalance between internal vapor pressure in the sheet and applied pressure. These works suggested that gradually decreasing the applied pressure at the end of the nip or increasing the ambient pressure as the sheet is decompressed could reduce the imbalance. Information that describes temperature and compression profiles in the nip is of interest because sheet temperature determines internal vapor pressure.

EXPERIMENTAL PROCEDURES

The measurement system we used to investigate linerboard compression and expansion during conventional wet pressing and impulse drying uses different pressure pulses. The work reported here improves upon that of Burton, et al. [3] and Burns, et al. [4] by simulating shoe press nips rather than roll press nips, and including a press felt in the nip rather than a rigid, porous water receiver.

Figure 1 shows a schematic of the press simulator.



1. Experimental setup of dynamic thickness measurement system on the MTS press.

The temperature of the platen of the electrohydraulic press was set from ambient to 350°C using a temperature controller. We placed the sheet with the felt and rigid plate on the top of the sensor housing and subjected it to a programmed press pulse. We used five sensors for displacement measurements of the perforated copper targets (25 mm thickness) which were positioned at the different levels in the sheet. Three of the targets were embedded in the sheet and the other two targets were positioned on the top and bottom of the sheet. The results reported in this work were obtained with 205 g/m² unbleached sheets with equidistant targets (five 41 g/m² layers).

When impulse drying was simulated, two thermocouples were placed on the top and bottom of the sheet. We measured temperature profiles by using thermocouples that were embedded into the sheet. The sheets were made from repulped linerboard that contained 30% old corrugated container (OCC). The repulped linerboard had a freeness of 660 mL CSF. Peak pres-

sure was about 5100 kPa, nip time was about 40 ms, and press impulse was 0.12 MPa sec.

RESULTS AND DISCUSSION

Compression during wet pressing and impulse drying

Figures 2 and 3 show examples of the sheet compression profiles at ambient and elevated temperatures. For convenience, we show transverse positions of the targets—as functions of the nip time—in normalized units as referenced to the initial thickness of the sheet. The dynamic thickness curves for both ambient and elevated temperatures provide evidence that the thickness minima occur toward the end of the nip. The figures further indicate that an increase in platen temperature results in:

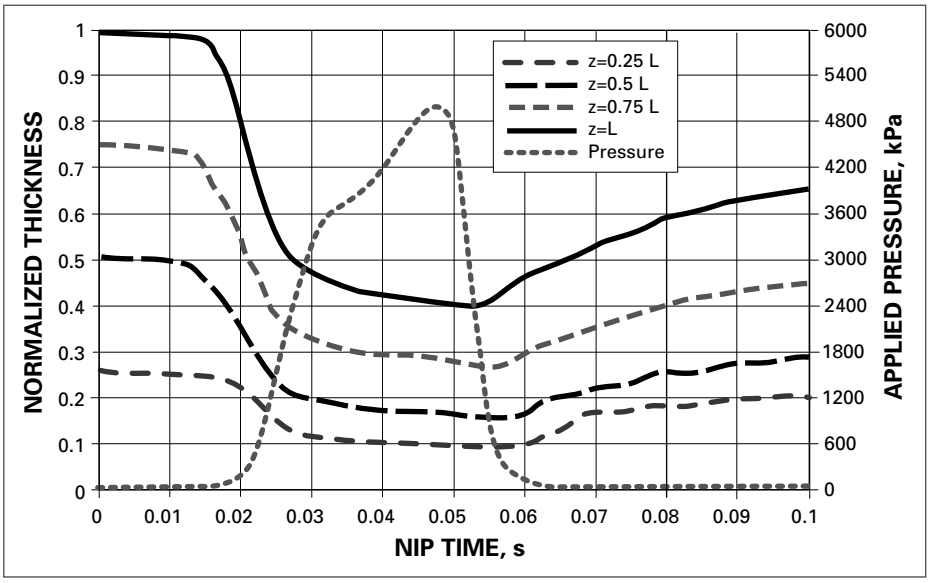
- higher compression of the sheet
- nonuniform densification of the impulse-dried sheet due to high compression of the top layer of the sheet
- lower sheet expansion during nip opening unless the sheet is delaminated.

The observed effects as to the impact of elevated platen temperature on the sheet compression in the nip support previous observations (Burton, et al. [3], MacGregor [5], Cutshall and Hudspeth [6]).

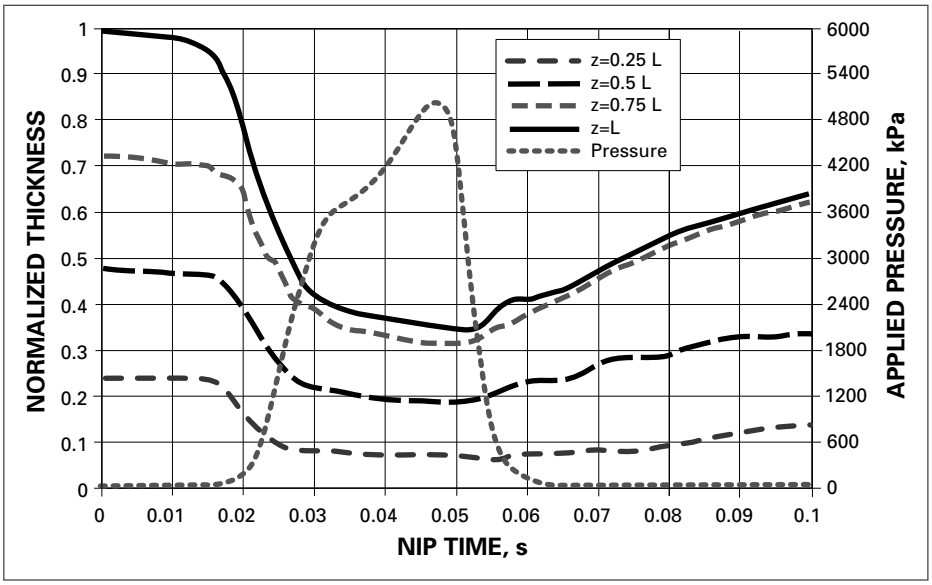
Compression intervals in the nip

Based on the sheet thickness vs. nip time data, we calculated compression rate curves for the sheets pressed at different platen temperatures. **Figure 4** shows an example of compression rate and applied pressure for pressing at room temperature. Analysis of compression rate curves for both wet pressing and impulse drying made it possible to identify four intervals in the nip:

- *Interval 1* is from the entrance of the nip to the maximum of the compression rate curve. During this period of the nip, the compression rate in the nip is high. The applied pressure is thought to be primarily balanced by compressed air contained within the pores.



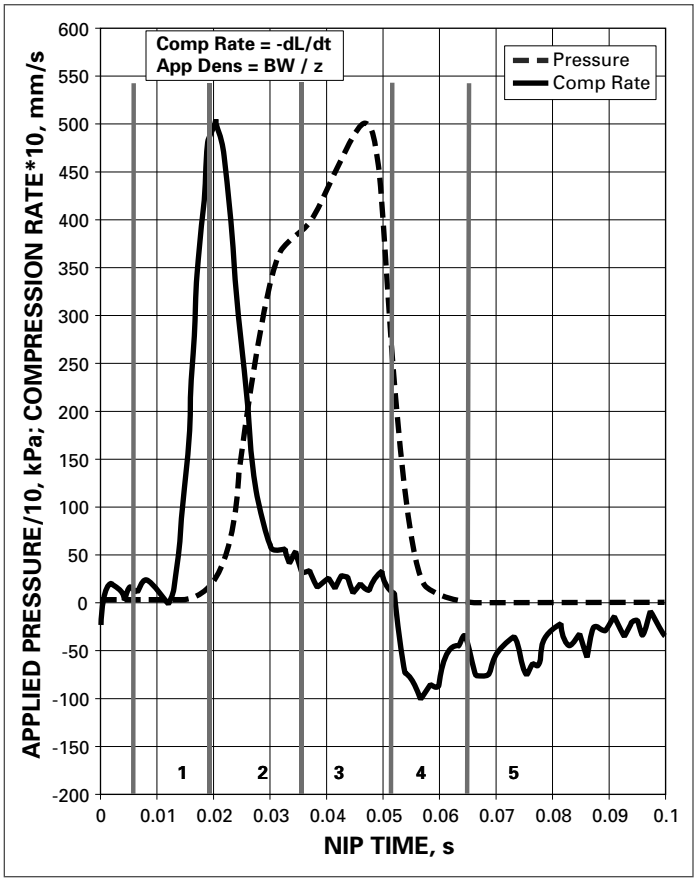
2. Sheet thickness vs. nip time at room temperature.



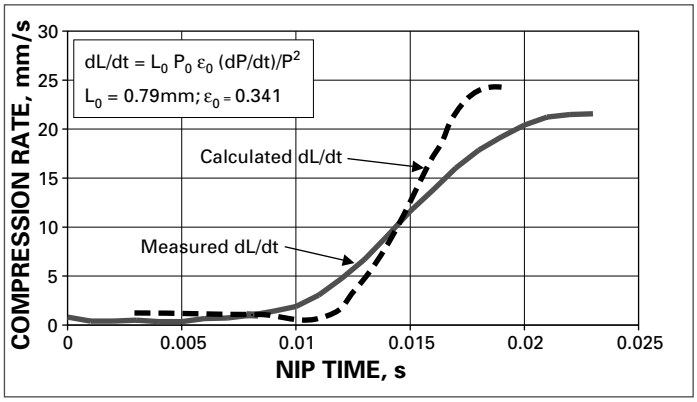
3. Sheet thickness vs. nip time at platen temperature of 300° C.

- *Interval 2* is from the maximum of the compression rate curve to the instant when the compression rate drops to a value close to zero. During this interval, water from the larger pores is removed from the sheet.
- *Interval 3* is from the point where the compression rate is close to zero (or a discontinuity in the slope of compression rate curve takes place) to zero slope of the compression curve in the nip. In this interval, water from the smaller pores (interfiber water) is removed from the sheet.
- *Interval 4* is from zero in compression rate to the exit of the nip. In this interval, the sheet expands. The rate of sheet expansion varies and has an extreme magnitude at some point of the expansion phase of the nip.

Wahlstrom [7] and Nilsson and Larsson [8] have identified similar intervals in the press nip in their fundamental works for transversal flow nip of a roll press. Burton, et al. [3] also showed similar compression intervals based on an experimentally measured apparent density curve. Using the information derived



4. Compression intervals in the press nip.



5. Experimental and calculated compression rates for pressing at room temperature.

from dynamic thickness measurements, we can identify the boundaries between the intervals and the acting mechanisms of water removal from the compression rate curve.

For this effort, we assume that compressibility of the sheet is mainly determined by compressibility of the air contained in the sheet in Interval 1 of the nip. We can then calculate the compression rate based on the equation of ideal gas for air at constant mass of air. By differentiating this equation with respect to time, we obtain the following expression for compression rate:

$$-dL/dt = L_o \rho_{oa} \varepsilon_o R T_o^* (dP/dt)/ P^2 = L_o \varepsilon_o P_o^* (dP/dt)/ P^2$$

where:

L_o , ρ_{oa} , ε_o are thickness, air density, and air porosity of uncompressed sheet;
T_o is sheet temperature, K;
R = 286.7 J/(kg K) is gas constant for air;
P_o = 101325 Pa is atmospheric pressure.

Absolute pressure must be used in the above formula by adding it to the gauge pressure of the measured applied pressure curve.

Figure 5 shows the experimental and calculated compression rate curves. There is a reasonable match between these two curves. The theory is useful in estimating the instant of time when the sheet becomes saturated and water removal from the sheet begins. Subsequently, the sheet compression rate determines water removal from the sheet.

Heat pipe process inhibits the likelihood of delamination in a decompressed hot sheet

We determined temperature profiles at platen temperatures of 100°C, 200°C, and 300°C. **Figures 6 and 7** show the temperature profiles for platen temperatures of 100°C and 300°C respectively, demonstrating significant difference in temperature profiles when the sheet is heated below and above the normal boiling point.

Figure 6 shows that at a platen temperature of 100°C, sheet temperature in both the compression and the decompression phase of the nip is controlled by heat conduction and convection of expressed water. The change of sheet temperature in the nip occurs more or less monotonically.

The temperature profile changes significantly when the sheet temperature exceeds the normal boiling point, which happens in the decompression phase of the nip. Sheet temperature profiles at a platen temperature of 300°C (Fig. 7) indicate an intense heat transfer process, which involves vaporization and condensation within the decompressed sheet. Such a process is usually termed a heat pipe process.

The heat pipe process based on the measured temperature profiles shown in Fig. 7 occurs in the following way. At the instant of time about 0.052 s, the applied pressure reduces below saturation pressure corresponding to the temperature on the top of the sheet (interface hot platen – sheet, z = L) and vaporization begins. This leads to rapid decrease of the temperature at the level of z = L. The vapor flows to the bottom of the sheet and once it reaches the level where the sheet temperature is below saturation point; the condensation occurs. This produces rapid rise of the temperature at the level of z = 0.75 L. It can be stated that vaporization – condensation occurs between levels of z = L and z = 0.75 L during the timeframe of 0.052 – 0.057 s (Interval 1).

As applied pressure further reduces, saturated vapor pressure at the level of 0.75 L attains the saturation point and boiling starts at the level of 0.75 L. The maximum temperature at the level of 0.75 L at time of 0.057 s indicates that the condensation is over and vaporization starts. This results in a rapid decrease of the sheet temperature at the level of 0.75 L. The vapor flows toward the bottom (colder portion) of the sheet and condenses at the level 0.5 L producing rapid rise of the temperature at the level of 0.5 L. This vaporization-condensation process happens during the timeframe of 0.057–0.064 s (Interval 2).

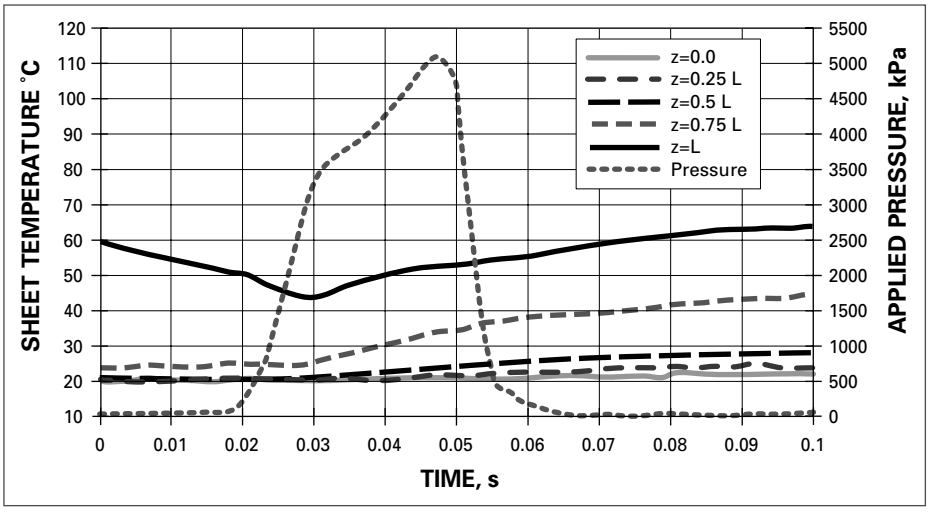
During the short timeframe from 0.052 s to 0.064 s, the temperature difference between the levels of z = L and z = ½ L drops from 70°C (140°C-70°C) to 16°C (110°C-94°C) due to intensive heat transfer by the vaporization–condensation mechanism (V–C in Fig. 7). In essence, vaporization-condensation zone propagates across the sheet, from hotter to colder portions of the sheet. In addition, the size of vaporization–condensation (or heat pipe) zone in z-direction decreases, because the sheet temperature and temperature gradient diminish. The vapor pressure gradient, which induces vapor flow and heat transport across the sheet, also reduces. Consequently, the vaporization–condensation process declines.

Thus, measured temperature profiles of the sheet subjected to pressing at platen temperatures of 300°C reveal that the decompression of the sheet is accompanied by evaporation and vapor flow from the upper hotter zone of the sheet toward the colder layer of the sheet, where condensation occurs.

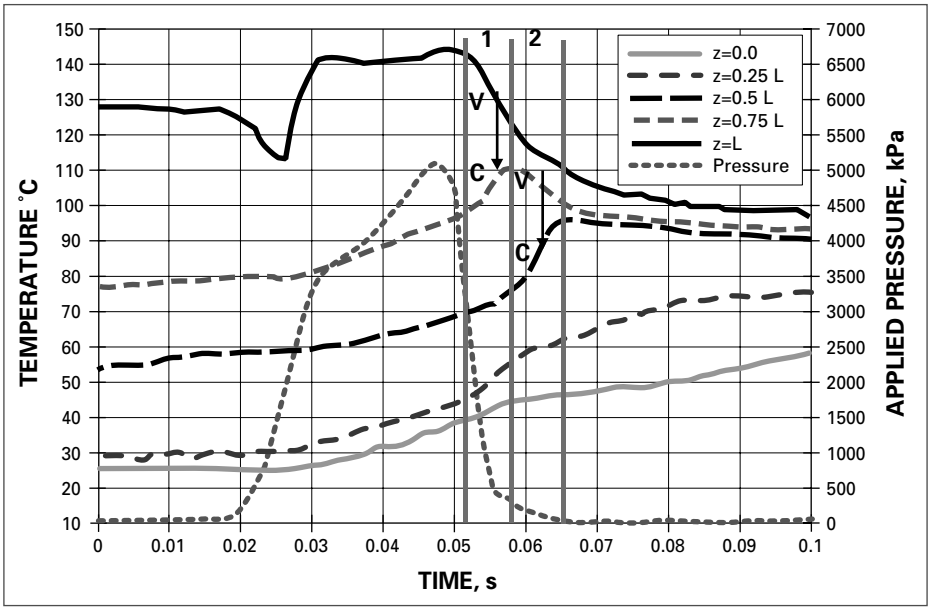
We identified the following phases of the heat pipe process, based on the measured temperature curves:

- Vaporization in the top heated part of the sheet and reduction of its temperature
- Vapor flow from the hotter, top part of the sheet to the colder, bottom part of the sheet due to a gradient of internal vapor pressure
- Condensation of vapor in the bottom part of the sheet and an increase of its temperature
- A drop in internal pressure, again triggering vaporization if the sheet temperature exceeds the saturation temperature, and a repeat of the process.

This process leads to a rapid evening out of the temperature across the sheet. If, during the decompression phase of the nip, the maximum sheet temperature is brought down below 100°C, delamination should not take place. Otherwise, a balance between internal forces applied to the fiber network and the transversal wet strength of the sheet determines the likelihood of delamination.



6. Sheet temperatures vs. sheet thickness at platen temperature of 100°C.



7. Sheet temperatures vs. sheet thickness at platen temperature of 300°C.

The proper design of the decompression process is an essential factor in inhibiting delamination. The time required to decompress the sheet without causing delamination can be estimated from simple physical considerations based on the known amount of heat to be removed from the hot, top part of the sheet by the vaporization-condensation process. In that calculation, Darcy's law can be used to determine the vapor flow velocity (See related article, p. 12)

Such an estimate yielded a required decompression time of about 9 ms. Orloff, et al. [9] reported that delamination occurred at a decompression time of 4 ms. At the next selected decompression time of 19 ms and higher, delamination was prevented.

CONCLUSIONS

Application of a dynamic thickness and temperature measurement system allowed the development of new insights concerning sheet compression and expansion during wet pressing and impulse drying.

The main findings are as follows:

- Major differences in the sheet compression profiles at elevated and conventional temperatures exist.
- Sheet compression measurements and the estimated compression rate curve

served to identify compression intervals associated with expression of intrafiber and interfiber water out of the sheet.

- Controlled sheet decompression at the end of the nip is a significant factor for inhibiting delamination at a high platen temperature.

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DARCY'S LAW

Simply put, Darcy's law describes the rate of flow of water through porous media. It was developed by Henry Philibert Gaspard Darcy, a French civil engineer born June 10, 1803 in Dijon.

During his career, Darcy worked on well drilling and water transport projects, plus a variety of other public works. He later served as chief engineer for the Department of Côte-d'Or and as chief director for water and pavements in Paris. From research on the flow of water through sand in 1855 and 1856, Darcy developed his widely used, modified, and adapted equation.

Darcy's experiments measured the rate at which water flowed through a column of sand-a filter. The equation he formulated can be stated as $Q = KA[(h_1-h_2)/L]$ or $Q/A = -K[(h_1-h_2)/L]$, where:

Q = the rate of flow (volume/time)

K = coefficient of permeability or hydraulic conductivity

A = cross-sectional area

L = length of the filter material

(h_1-h_2) = measured pressure difference

Isaak Rudman and David I. Orloff, in "Dynamic thickness and temperature measurements during wet pressing and impulse drying" [*TAPPI J*, 1(5): 1x(2002)], use Darcy's law to determine vapor flow velocity to estimate the time required to decompress a sheet without causing delamination.

Mark A. Paradis and coauthors, in "Determination of drainage resistance coefficients under conditions of known shear rate," a paper being edited for a future issue of *TAPPI JOURNAL*, give another example of how Darcy's law can be applied in pulp and in pulp and papermaking. The authors modify Darcy's law as follows to define the drainage resistance (a) of a paper stock as it is being filtered on the wet end of a paper machine:

$$\frac{\Delta P_m}{L} = av$$

In the above equation (ΔP_m) is the pressure drop across the fibrous mat that is building. The thickness of the mat is defined to be (L) when the superficial drainage velocity is (v). To estimate the drainage resistance (a), requires an apparatus that simultaneously measures the pressure drop (ΔP_m), the mat thickness (L), and drainage velocity (v) in real time.

For more information about Darcy and his work, and a translation of his 1856 report, visit <http://biosystems.okstate.edu/darcy/>. For further insights on the equation and its variants, visit <http://class.et.byu.edu/ce547/notes/darcy.pdf>

—Donald G. Meadows