Dynamic measurement of density-gradient development during wet pressing

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The modified press simulator will enable detailed research into the dynamic changes occurring within the sheet during wet pressing.

Wet pressing is a complex process involving the simultaneous compression of a wet fiber mat and the flow of water from that mat. The compression and water-removal aspects of the process have been the subjects of considerable investigation (*1-4*). Most nip-simulation methods rely on techniques and equipment that support *a posteriori* examination of the effects of process variables (nip residence time, applied pressure, etc.) on sheet structure and water removal. There is a growing recognition, however, that the ability to determine the sheet's response to these variables as it passes through the nip would provide greater insight into both water removal and rewet mechanisms. Such an approach would also increase our understanding of how property development is affected by the changes in internal sheet structure that occur within the press nip. This aspect of wet pressing research has been largely ignored.

Literature review

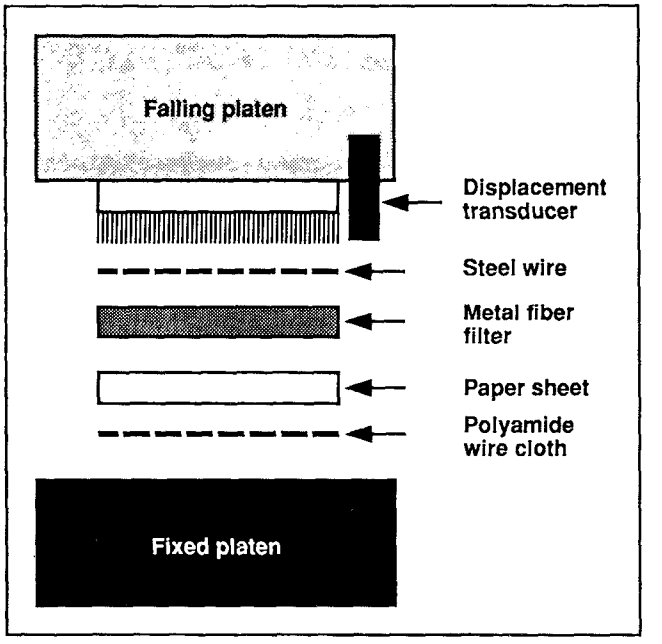
Previous investigations of the internal structural changes occurring within the sheet during wet pressing generally fall into two categories. The first category includes research focusing on sheet density or fines distribution after pressing. The literature describing these efforts is quite extensive and cannot be discussed here; an excellent review has been published by MacGregor (*5*).

The second category includes research based on dynamic measurement of either sheet thickness or the internal structure of the sheet during wet pressing. Measurement of dynamic changes in the sheet is significantly more difficult than measurement of static properties. Thus the number of reports in this second category is more limited. These reports are reviewed here in chronological order.

Davis *et al.* (*6*) made the first published attempt to measure dynamic thickness changes occurring inside the press nip of a wet-press simulator. The dynamic thicknesses of the sheet and the felt were measured from the positions of targets placed both at the sheet-felt interface and at the surface of the sheet. Two eddy-current proximity detectors were used to sense the distance of two targets from the surface of the press platen. The basic principle of operation of these probes involves inducing an electric current on the surface and within a metal target via a high-frequency electromagnetic field. These "eddy" currents produce a secondary magnetic field that reduces the intensity of the original magnetic field produced by the exciting coil of the transducer. Changes in the impedance of the exciting coil are sensed and converted into a signal directly proportional to the distance between the coil and target.

Carlsson (*7*) was primarily interested in determining the overall thickness change of the sheet obtained during wet pressing. For this work, he developed a servo-hydraulic platen press as a wet-press simulator. His press simulator

1. Carlsson's press-nip simulator



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was capable of producing long applied pressure pulses with low pressure tails for 75 ms or longer. The nip used by Carlsson, illustrated in **Fig. 1**, consisted of a stationary, solid brass plate on the bottom and a movable top platen. He placed a thin polyamide cloth between the wet sheet and the bottom platen to prevent fibers from blocking the hydraulic pressure sensor. (The hydraulic pressure sensor is not shown in Fig. 1.) Above the sheet was a metal fiber filter (water-flow receiver) and a 100-mesh stainless-steel wire. The height of the grooved upper head above the bottom plate was measured by a displacement transducer attached to the upper head. This was used to follow the compression and expansion of the sheet, a technique that was later used by several other researchers to determine the sheet thickness for the compression side of the nip (*8-10*).

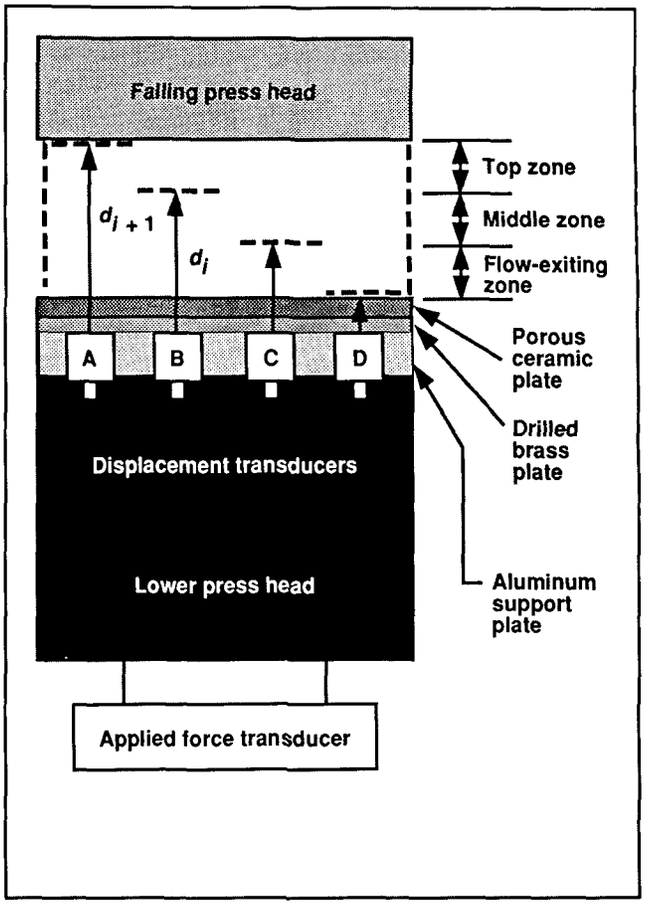
This particular press configuration does not provide a way to verify that the sheet follows the upper platen as it retracts from the sheet at the end of the press cycle. Also, the introduction of three other materials into the nip makes it very difficult to measure the actual change in sheet thickness.

Therefore, the accuracy of Carlsson's data for the sheet thickness on the expansion side of the press nip must be questioned. Dynamic sheet thickness must be measured at the interfaces of the sheet and must not be inferred from the height of the moving platen. This demonstrates the need to accurately define the end of the nip, where the sheet separates from the upper platen.

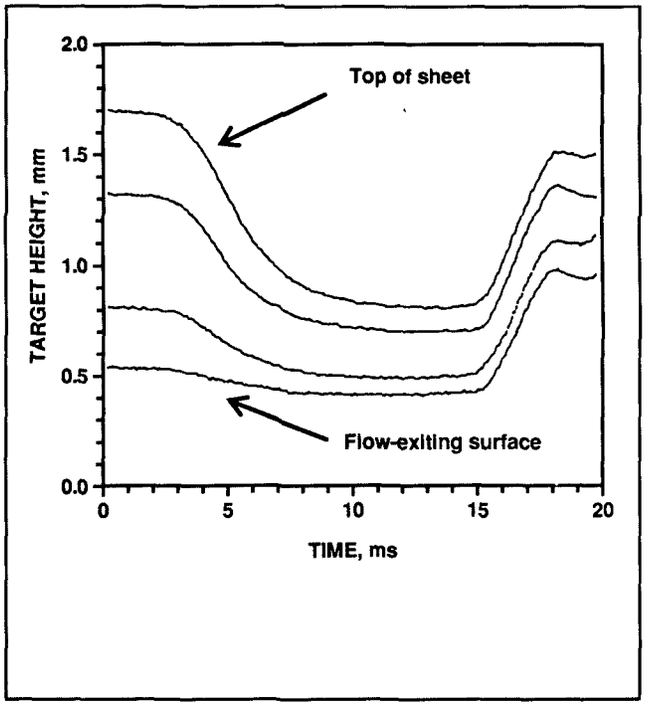
Burton (*11*) investigated the *z*-direction density profile development during impulse drying and developed equipment to measure dynamic thickness changes occurring within well-defined layers or zones of a sheet. This equipment was similar to that used by Davis *et al.*, but the lower press head was redesigned to follow the position of four targets instead of the two used by Davis. Burton's apparatus is shown in **Fig. 2**. Basically, there are six major components used in this press-simulator design. The upper press head is designed to fall freely from a predetermined height, and its mass can be changed to increase the peak applied pressure and the nip residence time. The lower press head or pedestal is supported by a force transducer used to measure the force applied to the sheet. The lower press head also contains the four proximity detectors used to measure the dynamic thickness changes of the zones in the sheet. The sheet contains four targets, which are positioned during the sheet-forming process, as shown in Fig. 2. The drilled brass plate that sits atop the proximity detectors receives excess water and supports a porous ceramic plate. This drilled brass plate was supported by an aluminum plate which had part of its surface machined away to provide support columns. The technique used to position the targets will not be described here, but the targets can be precisely positioned in the sheet without disturbing the sheet formation (*12*).

The data collected from Burton's equipment seem to be unable to resolve the problems of defining the true beginning and end of the nip or of establishing a nondeflecting baseline from which to make the thickness measurements. The inability to overcome these problems and a close inspection of the components of the lower press head used by Burton indicated that a new design would provide more realistic data.

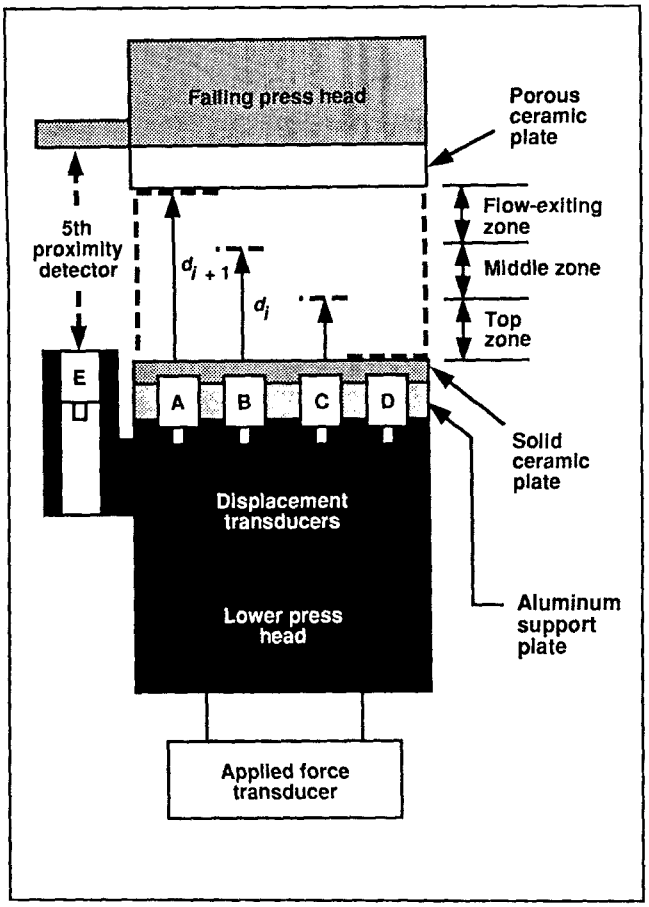
2. Burton's press-nip simulator



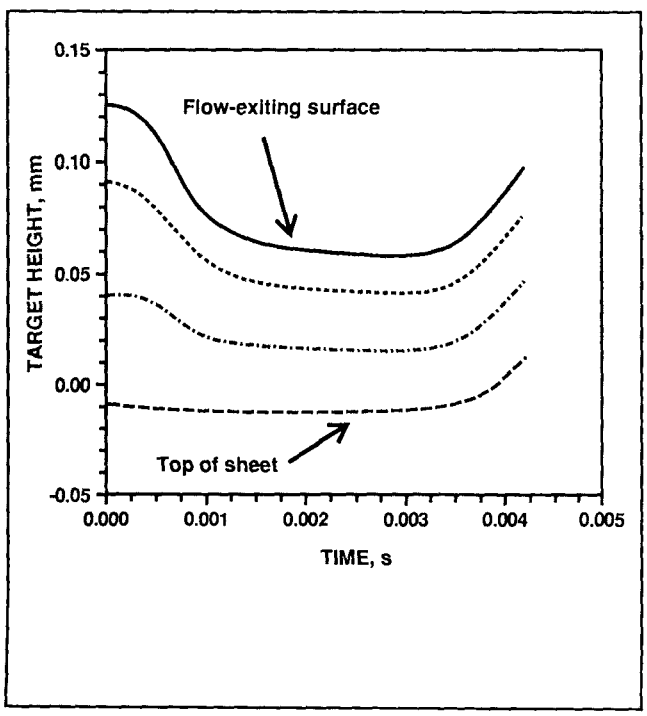
3. Burton's data, showing the target-height profiles for the four targets embedded in the sheet. Note downward displacement for the target placed at the interface between the sheet and the porous plate (flow-exiting surface).



4. Modified press-nip simulator with rigid ceramic plate surrounding proximity detectors. Porous ceramic plate is attached to falling platen.



5. Typical raw-data set of target-height profiles showing the height of each of the four targets from the redesigned press head.



Burton's equipment represented the state-of-the-art of press simulator design at the time, but the observed decrease in height of the target adjacent to the porous plate indicated that the porous plate or its supporting structure (the drilled brass plate) was deflecting upon application of a pressure pulse. The distribution of the supporting columns on the aluminum plate under the brass plate was nonuniform, which produced a different deflection of the brass plate around each proximity detector. The uneven deflection around each detector made it impossible to use the deflection observed with one of the proximity detectors as a correction factor for the other detectors. This lack of a rigid support for the porous ceramic plate and the drilled brass plate suggests that Burton's data should be questioned. We should note that, although an analysis of Burton's equipment revealed some unresolved problems, we believe that the techniques and concepts he developed are essentially sound. His contributions to the study of dynamic density development are still useful and establish a foundation for further investigations of the dynamic processes in the wet press nip.

Jaavidaan (*8*) was interested in determining the time available for rewet to occur in the press nip. He theorized, as did Wahlstrom (*13*) and Nilsson and Larsson (*14*), that the hydraulic pressure would reach atmospheric pressure at the minimum sheet thickness point. As the sheet began to expand from its minimum thickness, the hydraulic pressure would decrease until it reached a minimum value and then increase until it reached atmospheric pressure as the applied pressure dropped to zero. The minimum thickness point was believed to be the point at which rewet began, and the length of time from minimum thickness to the end of the applied pressure pulse was the length of time available for rewet to occur. The thickness increase from the minimum value was taken to be a direct indication of the amount of rewet in the expansion side of the nip.

Jaavidaan's experimental equipment was similar to Carlsson's in that the height of the upper platen (a porous metal plate or metal fiber filter) was used to measure sheet thickness. Jaavidaan's porous metal plate was rigidly attached to the upper press head so that it moved with the upper platen. This setup was in contrast to Carlsson's, where the porous metal plate was part of the sandwich in the nip. Since the porous metal plate moved with the press head, Jaavidaan had no way of determining whether the sheet surface and the upper platen remained in contact. His sheet-thickness technique measured only the height of the moving platen during the expansion phase. He appears to have assumed that the end of the nip occurred when the applied pressure reached zero. However, the sheet may have actually continued to expand in contact with the porous metal plate, even though there was no measurable applied pressure. In addition, the applied-pressure transducer and data-acquisition system used in these experiments were incapable of measuring the low-pressure tails of the applied pressure profile shown to exist by Beck (*15*).

By simply using the applied pressure profile to determine the beginning and end of the nip, Jaavidaan neglected a significant quantity of information about the early compression and late expansion of the sheet. This demonstrates once more the need to define the beginning

and end of the nip by knowing the positions of the sheet interfaces and their relation to the height of the upper platen as it retracts. Because Jaavidaan's equipment was incapable of realistically determining the end of the nip, calculations of the time available for rewet based on his data would likely be incorrect. In addition, Jaavidaan's correlation of the minimum thickness point with the onset of the negative hydraulic pressure is not validated by the data presented, since he did not measure the hydraulic pressure.

Objective of this work

Past experimental work

Most wet-pressing research has involved static measurement of paper samples. Of the few studies involving dynamic measurement, most have focused on the changes in thickness as the sheet passes through the nip. Burton was the first to attempt to investigate the changes in the internal structure occurring during wet pressing. The equipment that he developed for studying changes in the sheet's internal structure was a significant accomplishment, although flaws in his equipment design seem to have undermined the collection of accurate data throughout the press cycle. Therefore, to study the changes in the internal structure of the sheet during wet pressing, we must modify the equipment that Burton developed and correct any apparent deficiencies in the design.

Modification of earlier approach

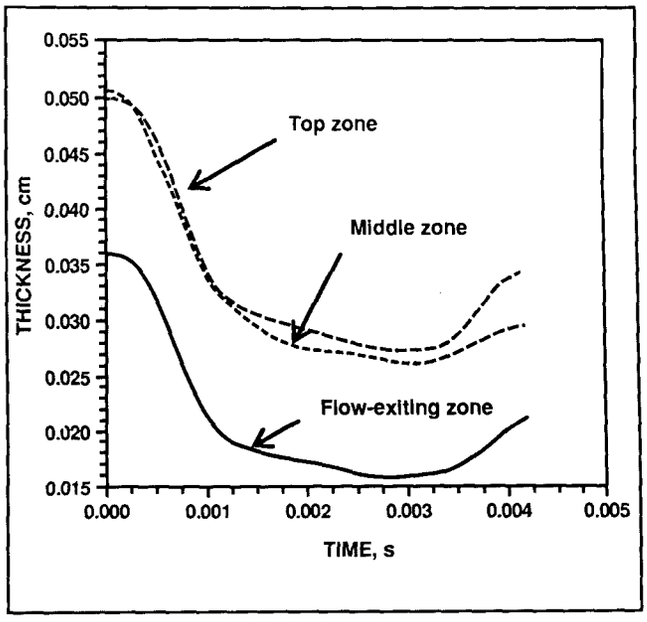
The objective of this work was to examine the changes in the internal structure of the sheet during wet pressing by accurately measuring the dynamic changes in thickness of three zones of the sheet. To satisfy this objective, the dynamic thickness-measurement equipment developed by Burton was modified. The modified equipment is capable of defining the true beginning and end of the nip, and the ambiguities created by deflection of the porous plate and its drilled brass supporting plate have been eliminated. Thickness measurements are made relative to a baseline that changes little upon application of force or pressure.

Experimental approach

Design of a new press simulator

One of the underlying assumptions in all the previous work involving the use of the porous ceramic and drilled brass plates was that the brass plate provided a rigid, nondeflecting support for the porous plate. It became apparent from early repetition of Burton's work that this was not the case. Evidence that the aluminum plate was not providing uniform support for the brass plate and the porous plate can be seen in a sample of Burton's data, presented in **Fig. 3**. The profile for the target mounted on the bottom of the sheet (the flow-exiting surface in contact with the porous plate) shows a marked decrease in height above the proximity detector upon application of a load. As the load is released and the platen moves away from the sheet, the sheet either begins to expand or is actually being pulled apart by mechanical surface adhesion of the sheet to the smooth upper platen and the porous plate on the bottom. Burton did not perceive the nonuniform support of the aluminum plate when he measured the behavior of the wet fiber web. Unfortunately, this problem introduces an element of doubt regarding the accuracy of his observations. Despite this, many aspects of his study are still valuable in terms of developing a better understanding of the fundamental processes involved in impulse drying.

6. Calculated change in thickness of each zone of the sheet in real time.



Modification of Burton's equipment

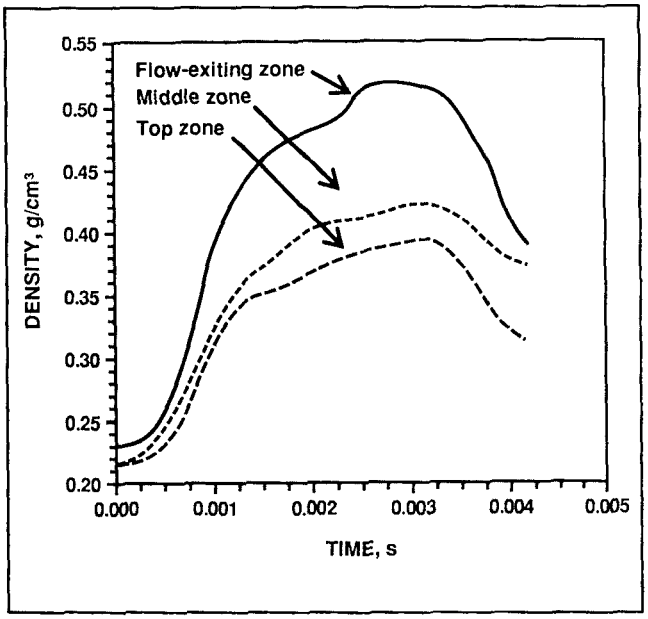
Given the problems with Burton's equipment, it was apparent that the press simulator would have to be completely redesigned. The effectiveness of each redesigned portion of the apparatus in the press simulator was confirmed before we proceeded to evaluate the next component. Using this approach, we were able to find and correct several minor problems that had previously gone undetected.

There are three essential requirements for accurate observation of the fibrous mat's thickness during wet pressing.

1. The porous plate must not be compressible. If it is compressible, this must not interfere with the resultant measurements.
2. The position of the target on the bottom of the sheet and its position relative to the other targets is critical to accurate measurement of the compression and expansion behavior of the wet fiber web.
3. The beginning and end of the nip must be defined precisely.

The compression of the porous ceramic plate used by Burton was found to be negligible under the loads used in his study. Regarding the second requirement, we have already noted that the lack of support in the brass plate affected the position of the target on the bottom of the sheet. The eddy-current proximity detectors can accurately follow the compression and expansion behavior of the fiber

7. Calculated change in density of each zone of the sheet in real time. The density of the flow-exiting zone is significantly greater than that of the other two zones.



web in the wet press, but suitable precautions must be taken. To fulfill the design requirements, Burton's falling-weight press simulator was modified, as shown in **Fig. 4**.

The 1.67-2.0-mm-thick (0.060–0.080 in.) porous ceramic plate used by Burton (shown as part of the bottom pedestal in Fig. 2) was replaced with a 9.5-mm-thick (0.375-in.) plate of the same material. This ceramic plate was considerably thicker than the measuring range of the proximity detectors, so the ceramic plate was mounted on the falling platen, as seen in Fig. 4. The supporting structure for Burton's porous ceramic plate was a drilled brass plate, which rested on a machined aluminum plate. The aluminum plate was machined to provide flow paths for the excess water that might pass through the drilled brass plate. Unfortunately, the aluminum plate provided nonuniform support for the brass plate. This problem led us to determine that the supporting structure for the sheet needed significantly greater compressive strength and flexural stiffness while maintaining its transparency to the proximity detectors. These requirements led us to experiment with machinable, solid, glass-based ceramics. A material from Cotronics Corp. (Brooklyn, N.Y.) was selected because of its high compressive and flexural strengths. A 0.25-in.-thick plate of glass ceramic was machined to allow recessed mounting of the proximity detectors, as shown in Fig. 4. Without recessed mounting, the plate's thickness would have exceeded the measuring range of the proximity detectors.

The porous ceramic plate and the brass plate with its supporting aluminum plate (Fig. 2) were replaced with the glass-based ceramic plate and a 0.5-in.-thick aluminum supporting plate in which the four proximity detectors were mounted (Fig. 4). This new aluminum plate provided a rigid, flat support for the glass ceramic plate, as seen in **Fig. 5**. The target-height profile for the target adjacent to the solid, glass ceramic plate (the top of the sheet in the modified press nip) shows virtually no deflection, indicating that the supporting structure meets our requirements. The rigidity of the lower press head eliminated the deflection observed with Burton's press head (Fig. 3). With a rigid lower press head, the positions of the four targets during wet pressing could be measured with confidence. A typical target-height profile from the redesigned press head is discussed later in this article.

The third requirement for accurate thickness determination is specific to the platen press simulator. The precise definition of the beginning and end of the nip has been lacking in all of the previous press-simulator designs. Definition of the precise moment at which the falling platen contacts the sheet and when it separates from the sheet requires that we know the exact position of both the falling press head and the target at the interface between the falling head and the sheet. To determine the exact position of the falling press head during a press cycle, a fifth proximity detector was mounted external to the lower press head, as seen in Fig. 4. This detector follows the position of the falling press head. Our definition of the beginning of the nip is the point at which the height of the falling press head is equal to that of the uppermost target in the sheet. The end of the nip is defined as the point at which the falling platen height becomes greater than that of the uppermost target.

The four displacement transducers are of the eddy-current type (KD-2310-4S) manufactured by Kaman Instrumentation Corp. (Colorado Springs, Colo.). These were used to track the motion of the metal targets (copper grids) during dynamic compression and expansion. The transducers have a measuring range of 4.0 mm (0.160 in.), with a resolution of 0.01% of full-scale calibration. Accurate calibration over a measurement span of 3.0 mm (0.120 in.) was done with a special micrometer with a nonrotating spindle. The micrometer with its attached target is accurate to within 6 μm. The transducers are calibrated while rigidly mounted in the lower head prior to each set of compression tests. The typical calibration curve of displacement vs. voltage is linear, with a correlation coefficient of 0.9999+.

The lower platen or pedestal is supported by an impact-force transducer (PCB Pieziotronics, Inc.) that senses the total force applied to the pedestal by the falling platen. The load cell was calibrated at the factory and is rated for loads up to 225 kN (50,000 lb • f). The lower resolution limit of the data-acquisition system used to measure the applied pressure in these experiments was 8.2 kPa (1.2 psi), thus allowing an 8.2-kPa change in applied pressure to be recorded. A high-strength 7575-aluminum alloy was used for the lower pedestal to minimize the mass attached to the load cell.

During operation, the lower pedestal supports the web while it is compressed by the falling platen. As the falling head (platen) strikes the sheet, water is expressed from the sheet into the porous ceramic plate used as a flow receiver. Use of the rigid ceramic plate limits the press nip to a single compressible material (the sheet) and contributes to a uniform pressure distribution on the sheet. The instrumented pedestal with its four proximity detectors and impact-force transducer provided the data needed to determine sheet behavior during wet pressing.

The dynamic density profile is calculated from the dynamic thickness measurements of specific zones having

a known basis weight. The targets are embedded in the sheet at various levels during sheet formation and are thin (0.0254 mm) relative to the total sheet thickness (wet uncompressed 1.52 mm). During consolidation, the integrally embedded targets move with the surrounding fiber network in response to dewatering and densifying forces. The target displacements are recorded from the transducers mounted in the lower head. The dynamic density of each zone is then calculated from adjacent target separation distances and the zone basis weight. The relationship for the dynamic density calculation is as follows:

$$\rho_i = BW_i/(d_{i+1} - d_i) \quad (1)$$

where

ρ_i = apparent density of the ith web zone, g/cm^3

BW_i = basis weight of the ith web zone, g/cm^2

d_{i+1} = distance to target above the ith web zone, cm

d_i = distance to target below the ith web zone, cm.

Preliminary results

A typical raw target-profile data set from the redesigned press head is shown in Fig. 5. The data show the dynamic height profile for each of the four targets embedded in the sheet, as shown in Fig. 4. The profile from the fifth detector is not shown. The profile of the target adjacent to the solid ceramic platen shows very little change in height up to the point where pressure is released. The slight decrease in height of the target adjacent to the solid ceramic plate was due to a slight difference in thickness across the plate, which was later corrected. The total height change of this target is less than 0.0508 mm (0.002 in.) over the entire applied pressure pulse (up to 6.89 MPa). Comparison with the same target in Fig. 3 shows a significant reduction in the downward movement of the target during wet pressing. The compression and expansion profiles shown in these two figures are very similar with the noted exception of the bottom target.

It is apparent from Fig. 5 that the equipment modifications have significantly simplified the analysis of the data. The data manipulation consists of calculating the zonal thickness change simply by subtracting the respective target profiles shown in Fig. 5. There is no longer a need to correct any of the thickness measurements for compression or flexing of the supporting plate. Using the modified simulator, it is possible to calculate the dynamic density of each zone (and thus overall sheet density) for sheets where the basis weight of each zone is known.

The dynamic or real-time thickness change was calculated for each zone and is shown in **Fig. 6**. The dynamic density development (or loss), shown in **Fig. 7**, was calculated from the basis weight and the measured change in zone thickness. Figure 7 shows that the density of the flow-exiting zone develops at a much faster rate and to a much greater extent than the other two zones. The difference in the densities of the flow-exiting zone and the other two zones (defined in Fig. 4) tells us that the middle and top zones do not dewater to the same extent as the flow-exiting zone. The uneven dewatering leaves both density and moisture gradients across the sheet. As the zones expand, most of the density developed in the flow-exiting zone is lost. At this point in time, it is premature to speculate on the effects of the density loss or how it affects rewet and property development.

The ability to dynamically measure density development during wet pressing provides insight into the changes that occur within the sheet as it passes through the nip. The effect of these changes on property development for the entire sheet is a subject for future research.

Conclusion

The modified press-nip simulator was developed to measure dynamic internal structural changes within the wet web. This device should prove to be a useful tool for examining the wet-pressing process. The simulator will be used to investigate the effects of:

- Nip residence time and peak applied pressure on the internal structure of the sheet
- Mechanical surface adhesion on the loss of sheet density in the expansion phase and its effect on rewet
- Internal structural changes on property development during wet pressing.

Preliminary data indicate that the density of the flow-exiting side of the sheet is significantly greater than the rest of the sheet. Insight into the effects of process variables on the compression and expansion of the sheet and on water distribution within the sheet will eventually lead to a better understanding of the fundamental processes occurring in the wet press. Knowledge of these processes will foster development of press designs that promote efficient dewatering of the wet web while maintaining or enhancing desired sheet properties.□

Literature cited

1. Ceckler, W. H. and Thompson, E. V., Wet pressing project final report, DOE/CS/40064-3(DE83009342), University of Maine, Orono, Aug. 24, 1982.
2. Ceckler, W. H. *et al.*, 1980 Engineering Conference Proceedings, TAPPI PRESS, Atlanta, p. 63.
3. Hoering, J. *et al.*, Proceedings of 1982 International Water Removal Symposium, The Institute of Paper Chemistry and the Technical Section of the Canadian Pulp and Paper Association, Vancouver, B.C., p. 99.
4. Chang, N. L., 1978 Engineering Conference Proceedings, TAPPI PRESS, Atlanta, p. 93.
5. MacGregor, M. A., Transactions of the Ninth Fundamental Research Symposium, The Fundamentals of Papermaking, BPBIF, Cambridge, England, Sept. 1989, p. 511.
6. Davis, E. J., Stratton, R. A., and Chang, N. L., J. Pulp Paper Sci. 9(3): TR68(1983).
7. Carlsson, G., Some fundamental aspects of wet pressing of paper, Doctoral dissertation, The Royal Institute of Technology, Stockholm, Sweden, 1983.
8. Jaavidaan, J., Experimental and theoretical study of two phase flow through compressible porous media with application to sheet rewetting in wet pressing of paper, Ph.D. thesis, University of Maine, Orono, 1987.
9. Jantunen, J., Transactions of the Eighth Fundamental Research Symposium, Papermaking Raw Materials, BPBIF, Oxford, England, Sept. 1985, p. 133.
10. Szikla, S. and Paulapuro, H., J. Pulp Paper Sci. 15(1): J11(1989).
11. Burton, S. W., An investigation of *z*-direction density profiles

development during impulse drying, Ph.D. thesis, The Institute of Paper Chemistry, Appleton, Wis., 1987.
12. Burns, J., Investigation of the constrained expansion phase of wet pressing, Ph.D. thesis in progress, The Institute of Paper Chemistry, Appleton, Wis., 1989.
13. Wahlstrom, P. B., Pulp Paper Mag. Can. 70(10): T349(1969).
14. Nilsson, P. and Larsson, K. O., Pulp Paper Mag. Can. 69(12): 66(1968).
15. Beck, D., 1986 Engineering Conference Proceedings, TAPPI PRESS, Atlanta, p. 105.

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