

Linerboard drying on a sheet-fed pilot impulse drying shoe press

David I. Orloff, Paul M. Phelan, and Jere W. Crouse

ABSTRACT: *The authors compare impulse drying to double-felted pressing for a range of process conditions. They report performance indicators including press dryness, STFI compression strength, and printability for both techniques and describe the influence of press roll surface, impulse, and nip residence time. The results confirm earlier laboratory tests that impulse drying is superior to double-felted pressing and can result in substantial benefits in product improvement, greater productivity, increased recycle use, and energy savings.*

KEYWORDS: *Compression strength, performance evaluation, pilot plants, printability, shock drying, shoe presses.*

Drying is the largest single energy use in the papermaking process. It accounts for approximately one-quarter of the total energy used. The intent of impulse drying is to increase papermaking energy efficiency by reducing the amount of water removed by conventional evaporative drying.

Impulse drying occurs when a wet paper web passes through a shoe press nip in which the press roll has a high temperature. A steam layer next to the heated surface grows and displaces water from the sheet very efficiently. The energy required for water removal is therefore considerably less than for conventional evaporative drying.

The increased dewatering during impulse drying allows improved productivity on existing machines that have dryer limitations. Impulse drying also provides increased densification and thermal enhancement of sheet bonding to develop equivalent or superior products at lower cost. Cost reduction comes from lower basis weight, use of higher yield or higher recycle content furnishes, and less refining.

A major reason for using impulse drying in the production of board grades is that impulse drying technology is an extension of shoe press technology. Almost all shoe presses installed throughout the world are on machines producing board

grades. A large fraction of the paper manufactured in the United States comprises board grades.

The introduction of impulse drying into the board grade market will probably parallel the introduction of shoe presses. Ten years after the first introduction in the early 1980s, shoe presses accounted for approximately 52% of U.S. and about 48% of world production of board grades. Using the rate of introduction of shoe presses as a basis with historical average production growth rates, yearly U.S. energy savings could increase to more than 0.84×10^{17} J (0.08×10^{15} Btu) within 30 years after introduction of impulse drying.

A troublesome component of the impulse drying process is sheet delamination (1). As the nip depressurizes, subcooled liquid water remaining in the sheet flashes to vapor and escapes through the heated surface of the sheet. When excessive amounts of energy transfer to the sheet, drag forces resulting from the escaping vapor can be high enough to overcome the cohesive forces holding the sheet together. The sheet then delaminates.

Controlling energy transfer to the sheet helps prevent sheet delamination. Low "thermal mass" press roll coatings reduce heat transfer to the sheet while maintaining high surface temperatures during early stages of the process. This ensures that most of the transferred energy forms steam that displaces liquid water. It avoids excessive steam formation leading to delamination.

Orloff is professor of engineering and director of the engineering and paper material division and Phelan is assistant scientist at the Institute of Paper Science and Technology, 500 10th St. NW, Atlanta, GA 30318, and Crouse is senior scientist at Beloit Corp., 1165 Prairie Hill Rd., Rockton, IL 61072.

I. Experimental conditions

Case	Pressing type	Roll cover	Felt	Pivot	Speed, m/min	Load, kN/m	Washwater
Con	Control	n/a	n/a	n/a	n/a	n/a	n/a
D1	D.F.	n/a	B	0	365	1050	Deionized
D2	D.F.	n/a	B	0	365	1489	Deionized
D3	D.F.	n/a	B	+2	365	1050	Deionized
D4	D.F.	n/a	S	0	365	1050	Deionized
D5	D.F.	n/a	S	0	365	1489	Deionized
D6	D.F.	n/a	S	+2	365	1050	Deionized
C1S	S.F.	C	B	0	365	1050	Deionized
C2S	S.F.	C	B	0	365	1489	Deionized
C3S	S.F.	C	B	+2	365	1050	Deionized
A1S	S.F.	A	B	0	365	1050	Deionized
A4S	S.F.	A	S	0	365	1050	Deionized
A5S	S.F.	A	S	0	365	1489	Deionized
C1	I.D.	C	B	0	365	1050	Deionized
C2	I.D.	C	B	0	365	1489	Deionized
C3	I.D.	C	B	+2	365	1050	Deionized
A1	I.D.	A	B	0	365	1050	Deionized
A2	I.D.	A	B	0	365	1489	Deionized
A4	I.D.	A	S	0	365	1050	Deionized
A5	I.D.	A	S	0	365	1489	Deionized
A6	I.D.	A	S	+2	365	1050	Deionized
A4F	I.D.	A	S	0	457	1050	Deionized
A5F	I.D.	A	S	0	457	1489	Deionized
A4H	I.D.	A	S	0	365	1050	"Hard"
A5H	I.D.	A	S	0	365	1489	"Hard"

Notes:

D.F. = Double-felted pressing
S.F. = Single-felted pressing
I.D. = Impulse drying
B = Felt type B
S = Felt type S

Roll surface temperatures were typically six temperatures at 25°C intervals.
All sheets had ingoing solids of 52%.
Repeats were typically four per case.
All sheets underwent steaming prior to impulse drying or double-felted pressing.

Literature review

Early laboratory-scale experiments

Early laboratory-scale work with a machinable ceramic showed that replacing the steel platen with a low "thermal mass" ceramic reduced sheet exit temperatures (2–4). Thermocouples placed at various locations within the linerboard sheet measured internal sheet temperatures during impulse drying. A steel platen gave internal sheet temperatures over 100°C as rapidly as 10 milliseconds. In contrast, the machinable ceramic restricted heat

II. Furnish compositions

Furnish case	Composition of top ply			Composition of bottom ply		
	Pulp type	CSF, mL	Weight, %	Pulp type	CSF, mL	Weight, %
WF1	HKSP	740	100	-	-	0
WF2	HKSP	600	100	-	-	0
WF3	HKDF	720	100	-	-	0
FD5	OCC	450	100	-	-	0
FD6	HKSP	740	20	HKSP	740	40
	-	-	-	OCC	600	40
FD7	HKDF	720	20	HKDF	720	40
	-	-	-	OCC	600	40

Notes:

HKSP = High kappa number southern pine
HKDF = High kappa number Douglas-fir

III. Fiber identification for various pulp samples

<i>Furnish</i>	<i>Pulp type</i>	<i>USWK, %</i>	<i>UHWK,%</i>	<i>Softwood species</i>	<i>Hardwood Species</i>
WF1	Southern pine, high kappa number	97-98	2-3	Southern yellow pine (hard cook), trace of semibleached kraft	Mixed, including gum, yellow poplar, and oak
WF2	Southern pine, high kappa number	97-98	2-3	Southern yellow pine (hard cook), trace of semibleached kraft	Mixed, including gum, yellow poplar, and oak
WF3	Douglas-fir high kappa number	100(-)	Trace	Douglas-fir, ponderosa or lodgepole pine or a mixture, balsam fir, hemlock, trace of cedar and white pine (hard cook)	Alder
FD5	OCC	n/a	n/a	Mixed unbleached kraft and semibleached kraft	Mixed kraft, unbleached, semichemical kraft, NSSC pulps, and mechanical pulps
FD6	HKSP and OCC	90-95	5-10 and semi-chemical	Mixed species including hard pine (southern yellow pine, ponderosa pine, lodgepole pine, and mixtures, etc.), Douglas-fir, balsam fir, and hemlock	Mixed including gum, oak, yellow poplar, and maple
FD7	HKDF and OCC	90-95	5-10 and semi-chemical	Mixed species including hard pine (southern yellow pine, ponderosa pine, lodgepole pine, and mixtures, etc.), Douglas-fir, balsam fir, and hemlock	Mixed including gum, oak, yellow poplar, and maple
Notes:					
USWK		= Unbleached softwood kraft			
UHWK		= Unbleached hardwood kraft			
NSSC		= Neutral sulfite semichemical			

IV. Fiber dimension

<i>Furnish case</i>	<i>Pulp type</i>	<i>Kappa number</i>	<i>Top ply, CSF, mL</i>	<i>Length, mm (arith)</i>	<i>Length, mm (LW)</i>	<i>Length, mm (WW)</i>	<i>Width, mm</i>	<i>Perimeter, mm</i>	<i>Cell wall thickness,mm</i>	<i>Coarseness, mg/100 m</i>
WF1	S. pine	109.2	740	2.52	3.21	3.73	36.6	87.2	3.5	36.0
WF2	S. pine	109.2	600	1.78	2.47	3.07	34.8	83.7	3.5	34.2
WF3	D.-fir	89.6	720	1.95	2.71	3.31	33.1	74.6	2.1	24.2
FD5	OCC	114.6	450	1.00	1.44	2.07	27.9	68.3	3.1	29.2
FD6	S. pine and OCC	n/a	740	1.80	2.68	3.43	33.7	79.8	3.1	29.4
FD7	D.-fir and OCC	n/a	720	1.66	2.52	3.20	34.5	78.6	2.4	26.8
Notes:										
LW		= Length weighted mean								
WW		= Weight weighted mean								

Impulse Drying

transfer to the sheet to reduce internal sheet temperatures.

Using a more practical plasma sprayed ceramic coated platen, water removal depended on initial temperature and impulse and was independent of platen thermal properties (4). This suggested that high water removal rates could be maintained while reducing excessive energy transfer to the sheet.

In the same experiments, platen thermal properties and peak pressure (impulse) influenced the critical impulse drying temperature (above which sheet delamination occurs). The work showed that the ceramic surface could operate at higher temperatures and pressures than the steel platen without inducing sheet delamination. This resulted in greater water removal from the sheet.

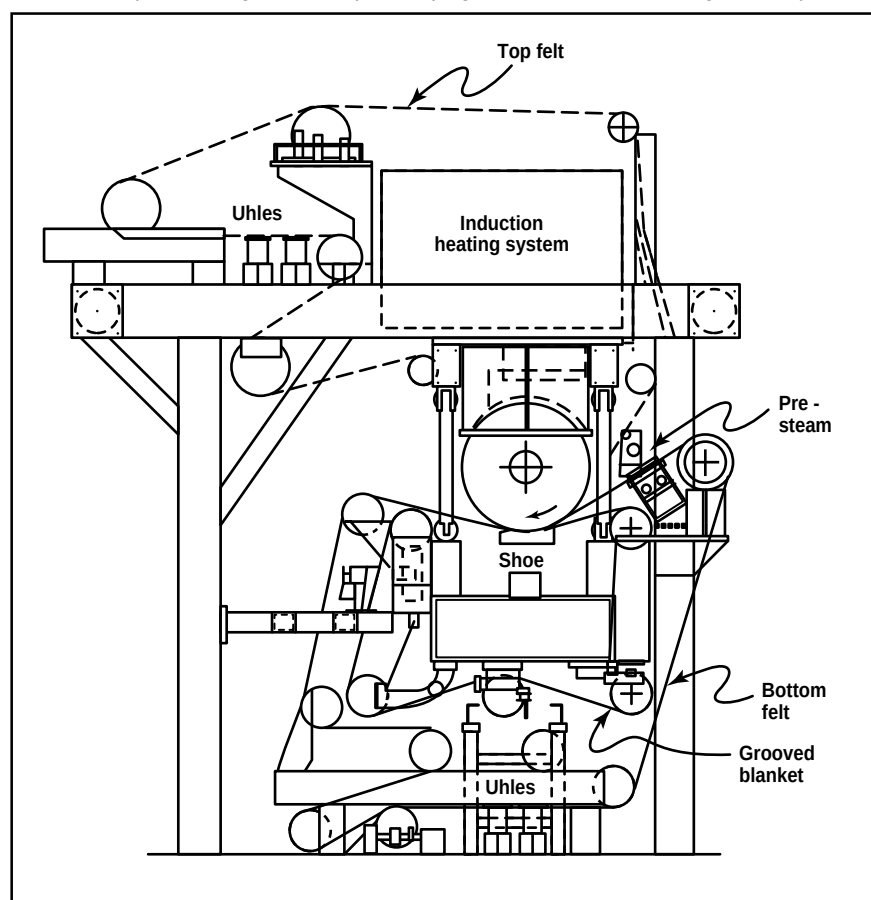
To explain this effect, there were additional experiments in which surface thermocouples determined how platen thermal properties affect energy transfer to the sheet (5). Energy transfer depended on peak pressure (impulse) for high "thermal mass" steel surfaces while being virtually independent of peak pressure (impulse) for the low "thermal mass" ceramic coated platen. At a given temperature and impulse, the ceramic surface transfers less energy to the sheet than the steel platen. It therefore is possible to postulate that ceramic surfaces avoid sheet delamination by decoupling heat transfer from wet pressing effects. The result is that the ceramic surface can operate at higher pressures without overheating the sheet. Concurrently, by transferring less energy, the ceramic surfaces can operate at higher temperatures.

Impulse drying under these conditions could increase sheet density to higher levels resulting in higher strength as measured by elastic modulus, Swedish Pulp and Paper Research Institute (STFI) compression strength, and burst strength. While ceramic surfaces achieve

V. Hydrodynamic specific surface

Furnish case	Specific surface, m^2/g	Standard deviation	Specific volume, cm^3/g	Standard deviation
WF1	1.3	0.5	1.0	0.2
WF2	3.1	0.7	1.1	0.1
WF3	2.3	0.8	1.1	0.1
FD5	10.5	0.6	1.0	0.0
FD6	1.4	0.2	1.2	0.1
FD7	2.0	0.3	1.1	0.0

1. Pilot shoe press configured for impulse drying and double-felted or single-felted pressing



higher density, the relationship between bond strength (specific elastic modulus) and sheet density was independent of platen material.

Roll press research

In 1991, impulse drying research shifted to demonstrating the process on a pilot roll press. The internal

structure of the plasma sprayed ceramic roll coating was similar to that of the earlier platen experiments. The ceramic coating had an effective "thermal mass" of $2000 \text{ W}\cdot\text{s}^{1/2}/\text{m}^2\cdot^\circ\text{C}$. An external source of infrared (IR) radiation controlled by an IR sensor heated the roll.

Pilot experiments performed at ingoing solids below approximately

VI. Critical temperatures, °C, for impulse drying on the X2 shoe press with upper and lower uncertainties

Case	Description	WF1		WF2		WF3		FD5		FD6		FD7	
C1	IPST–C/Felt B/0 Pivot/ 1050 kN/m	245	+50 -0	195	+50 -0	195	+50 -0	155	+35 -0	240	+50 -0	240	+50 -0
C2	IPST–C/Felt B/0 Pivot/ 1489 kN/m	245	+50 -50	245	+50 -0	195	+50 -0	150	+45 -50	245	+50 -0	150	+45 -0
C3	IPST–C/Felt B/+2 Pivot/ 1050 kN/m	150	+50 -50	150	+50 -0	150	+50 -0	145	+55 -45	245	+50 -0	245	+50 -45
A1	Beloit–A/Felt B/0 Pivot/ 1050 kN/m	200	+55 -0	175	+25 -0	175	+25 -35	145	+55 -0	200	+55 -0	145	+55 -0
A2	Beloit–A/Felt B/0 Pivot/ 1489 kN/m	200	+55 -0	175	+25 -0	175	+25 -35	120	+25 -0	200	+55 -0	145	+55 -0
A4	Beloit–A/Felt S/0 Pivot/ 1050 kN/m	155	+55 -0	155	+55 -0	155	+55 -0	130	+25 -0	130	+25 -0	155	+55 -0
A5	Beloit–A/Felt S/0 Pivot/ 1489 kN/m	155	+55 -0	155	+55 -0	155	+55 -0	100	+30 -0	155	+55 -0	130	+25 -0
A6	Beloit–A/Felt S/+2 Pivot/ 1050 kN/m/30 ms	150	+25 -0	150	+25 -0	150	+25 -0	120	+30 -0	150	+25 -0	150	+25 -0
A4F	Beloit–A/Felt S/0 Pivot/ 1050 kN/m	*	-	*	-	*	-	*	-	*	-	*	-
A5F	Beloit–A/Felt S/0 Pivot/ 1489 kN/m/30 ms	175	+25 -0	150	+25 -0	150	+25 -0	100	+50 -0	175	+25 -25	150	+25 -50
A4H	Beloit–A/Felt S/0 Pivot/ 1050 kN/m/hard water	175	** -0	175	** -0	150	+25 -0	100	+50 -0	175	+25 -0	150	+25 -0
A5H	Beloit–A/Felt S/0 Pivot/ 1489 kN/m/hard water	150	+25 -0	150	+25 -0	150	+25 -0	100	+50 -0	175	+25 -0	150	+25 -0
*	= <150												
**	= Not defined charge												

40% resulted in outgoing solids not significantly above that which conventional pressing technology could obtain. At ingoing solids above 40%, substantial improvements over conventional pressing were possible. An objective of the pilot trials was to determine the influence of furnish variables on impulse drying perfor-

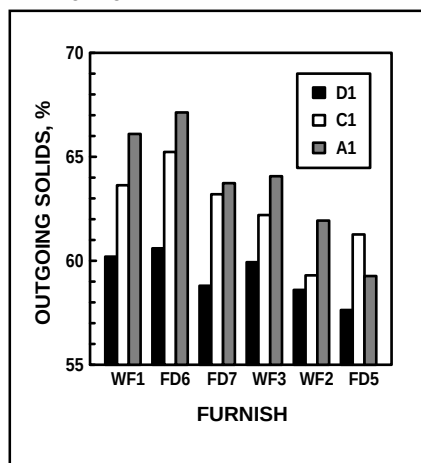
mance. Sheet permeability was investigated, since it influences conventional pressing processes. The out-of-plane permeability of single-ply linerboard was measured over a range of refining and pressing conditions (6). Permeability vs. sheet porosity data determined hydraulic specific surface. A low specific sur-

face means that the sheet is highly permeable. Increased refining increases specific surface. Pressing decreases specific surface.

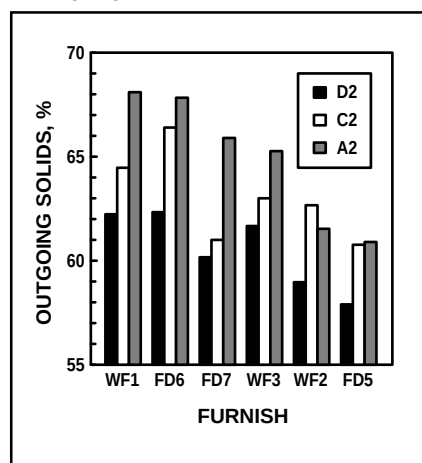
Permeability measurements involved two different linerboard furnishes (7) refined to 550 mL CSF from 740 mL CSF and pressed to 42% solids before testing. The single-

Impulse Drying

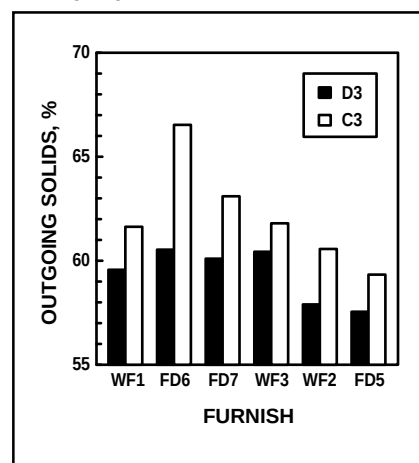
2. Outgoing solids for case 1



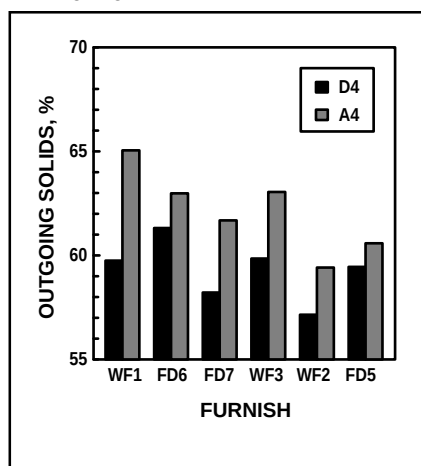
3. Outgoing solids for case 2



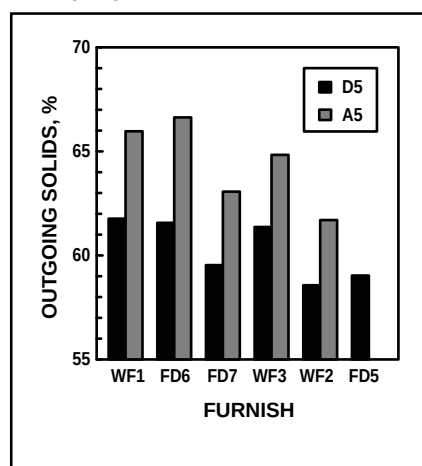
4. Outgoing solids for case 3



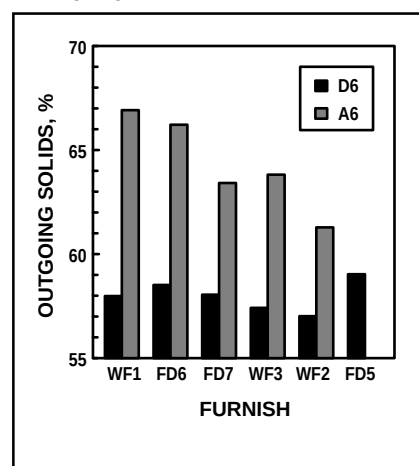
5. Outgoing solids for case 4



6. Outgoing solids for case 5



7. Outgoing solids for case 6



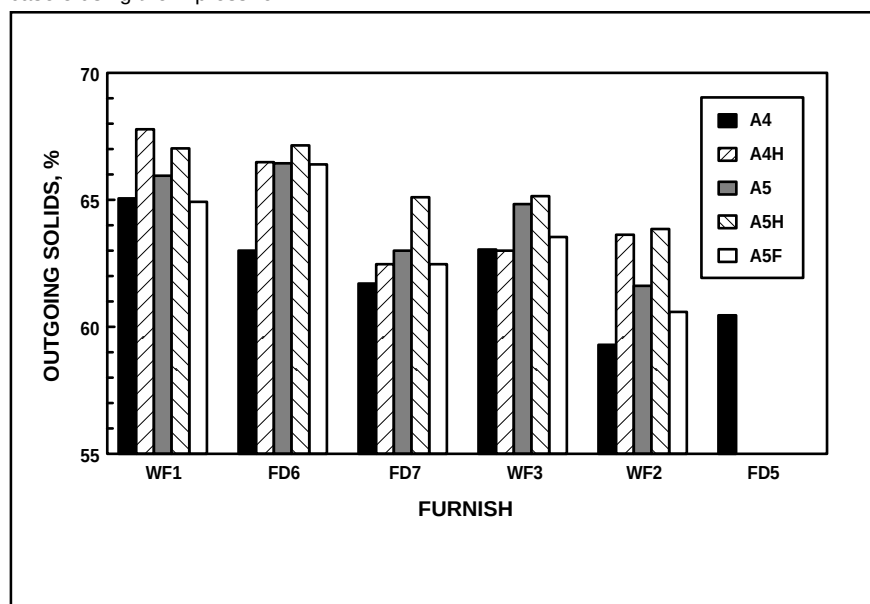
ply linerboard sheets for both furnishes underwent impulse drying on a pilot roll press. Critical impulse drying temperature decreased with increased specific surface (6, 7). Comparison of impulse drying at the critical temperature to single-felted pressing at the same impulse showed that the maximum benefit from impulse drying occurred with minimum specific surface.

Water removal depended on press surface temperature, impulse, and the specific surface of the sheet. Similarly, energy transfer during impulse drying only depended on press surface temperature (7, 8).

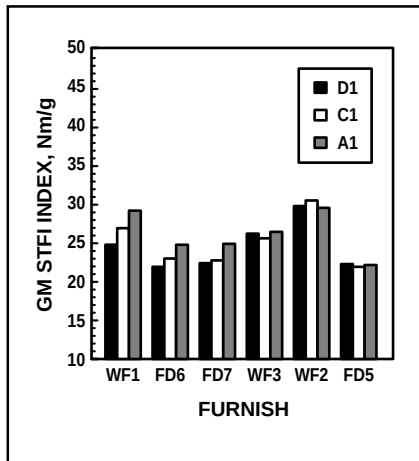
Laboratory-scale research

Commercial board grades are usually multi-ply sheets containing re-

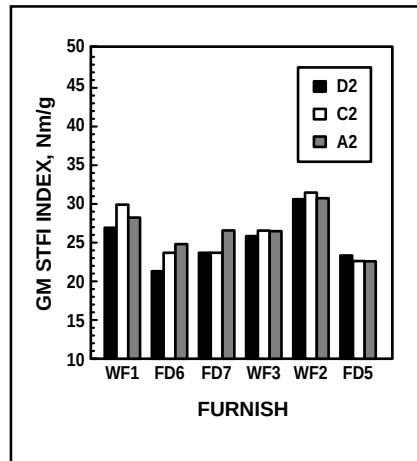
8. The effect of machine speed and felt wash water hardness on outgoing solids case 4 and case 5 using the A press roll



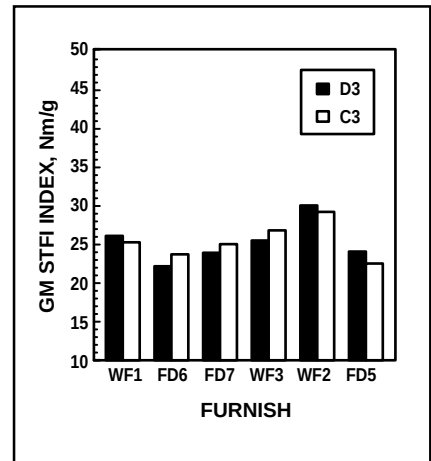
9. GM STFI index for case 1



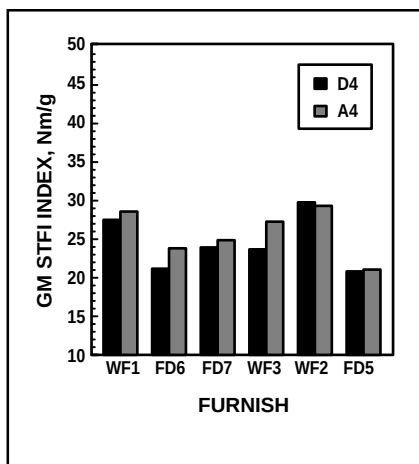
10. GM STFI index for case 2



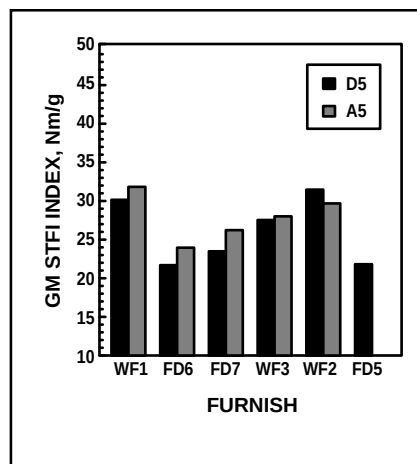
11. GM STFI index for case 3



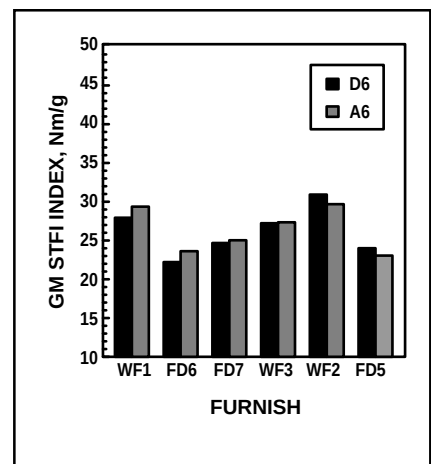
12. GM STFI index for case 4



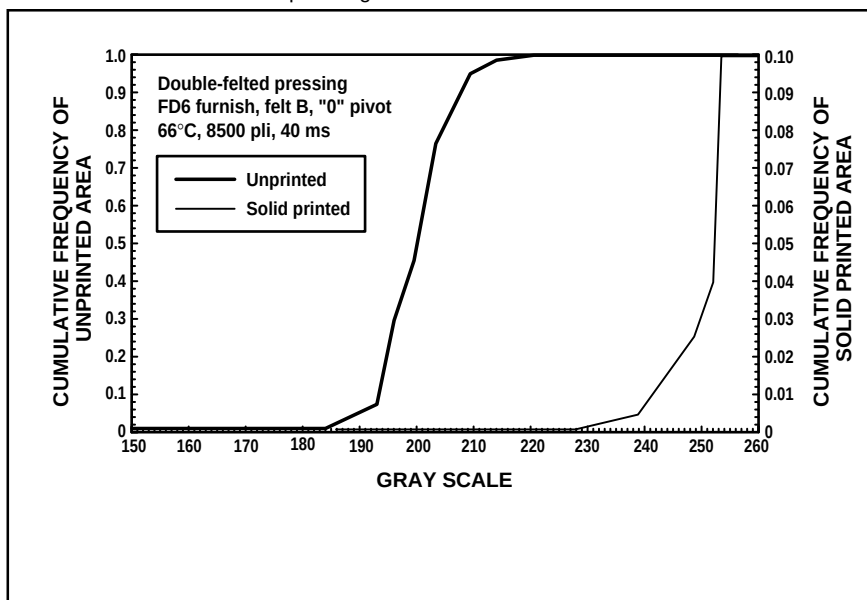
13. GM STFI index for case 5



14. GM STFI index for case 6



15. Cumulative frequency vs. gray scale for printed and unprinted regions of a two-ply sheet that underwent double-felted pressing



cycled fiber. Recent research has focused on applying impulse drying to these commercially important sheet structures. Laboratory-scale simulations have identified important pulp substitution variables and quantified the benefit of impulse drying (9).

Commercial linerboard is usually two- or three-ply using blends of virgin kraft and recycled fiber. In current practice, the fact that sheet strength properties decrease when recycle content increases limits the amount of recycled fiber included in linerboard. To achieve acceptable strength, mills either limit recycle content or further refine the recycle fiber. This negatively affects water removal and thus machine speeds.

Impulse Drying

Unacceptable physical appearance is a disadvantage of recycled fiber. To improve the appearance of liner using recycled fiber, U.S. manufacturers form a multi-ply sheet. The bottom or inner layer contains recycled fiber. Outer layers come from virgin pulp sufficiently refined to impart a good appearance to the product.

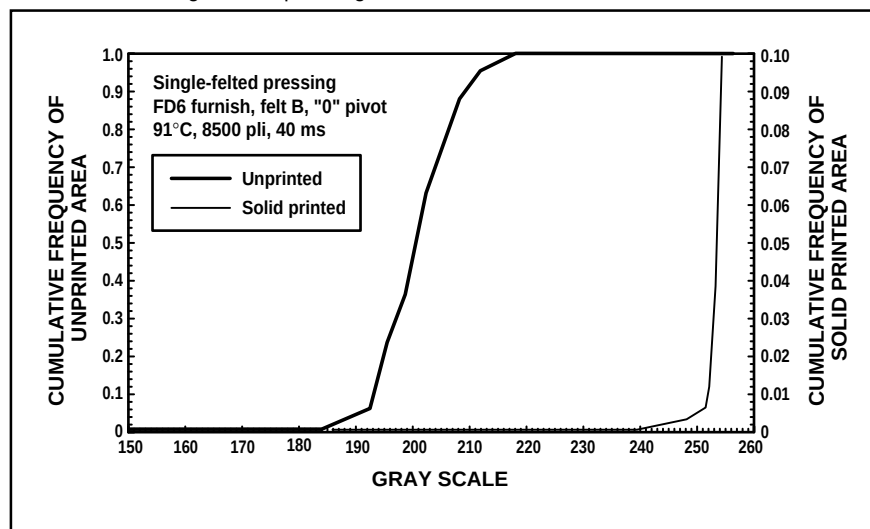
The experimental program had three groups. The first grouping investigated pulp species and kappa number. The second grouping examined blends of virgin kraft and OCC. The last set of experiments explored the influence of the composition and freeness of both top and bottom plies. The total basis weight of the sheets was constant at 205 g/m² (42 lb/1000 ft²).

The hydrodynamic specific surface of single component single-ply sheets varies with their CSF. High kappa number southern pine tended to be more permeable at a given freeness than low kappa number southern pine. In contrast, a low kappa number Douglas-fir was more permeable than high kappa number Douglas-fir. Contrasting the southern pine and Douglas-fir at high freeness showed that the southern pine tended to be more permeable.

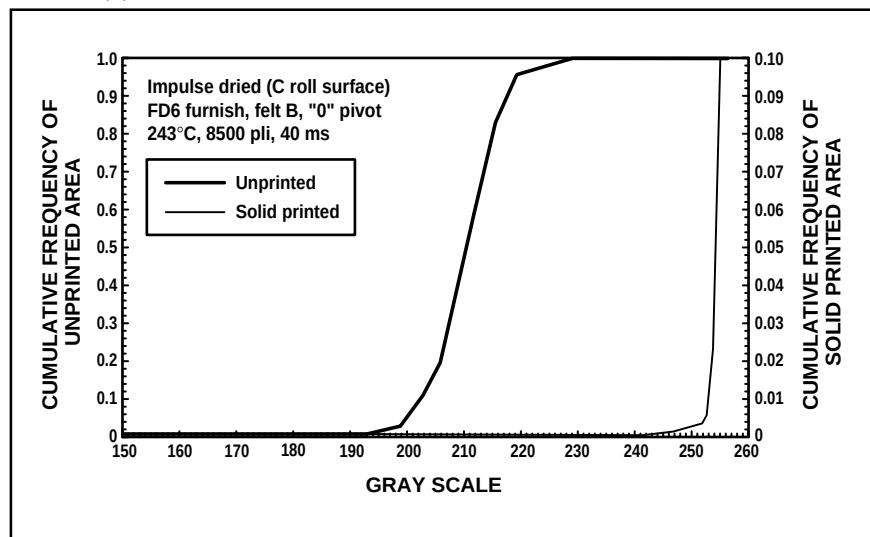
There was measurement of the hydrodynamic specific surface vs. freeness for the recycled OCC furnish. There was also measurement of the specific surface of two component blends of high kappa number southern pine with OCC as a function of the OCC content. Since specific surface was not a linear function of OCC content, it was possible to add as much as 60% OCC by weight without the specific surface increasing beyond 5 m²/g.

The electrohydraulic press simulated double-felted pressing and impulse drying of preheated sheets having 52% ingoing solids. Use of a programmable signal generator allowed the electrohydraulic press to simulate the same pressure history that a sheet might encounter in a

16. Cumulative frequency vs. gray scale for printed and unprinted regions of a two-ply sheet that underwent single-felted pressing



17. Cumulative frequency vs. gray scale for printed and unprinted regions of an impulse dried two-ply sheet



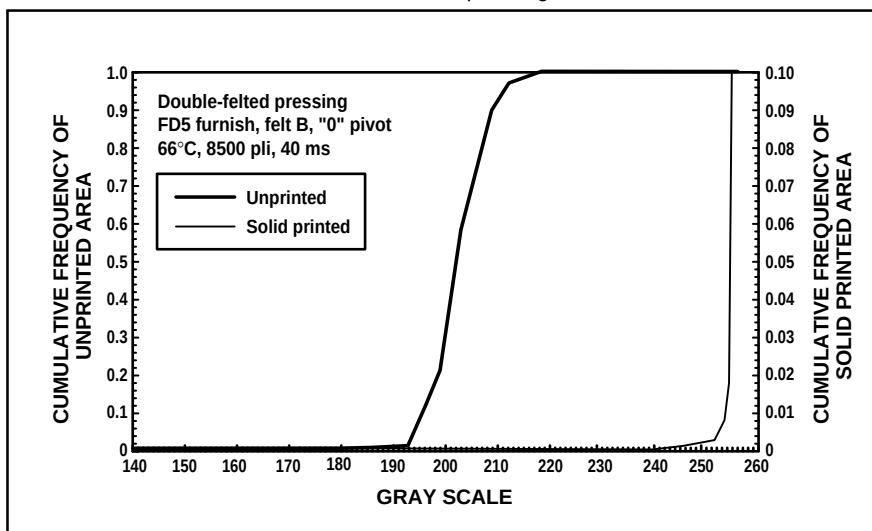
commercial impulse dryer configured on a shoe press.

Reports of critical impulse drying temperature were as a function of hydrodynamic specific surface. For single-ply sheets, the hydrodynamic specific surface was the measured value. For two-ply sheets, the hydrodynamic specific surface was the surface of the sheet in contact with the heated platen. Critical impulse drying temperature results compared well with previous results obtained on a pilot roll press (7).

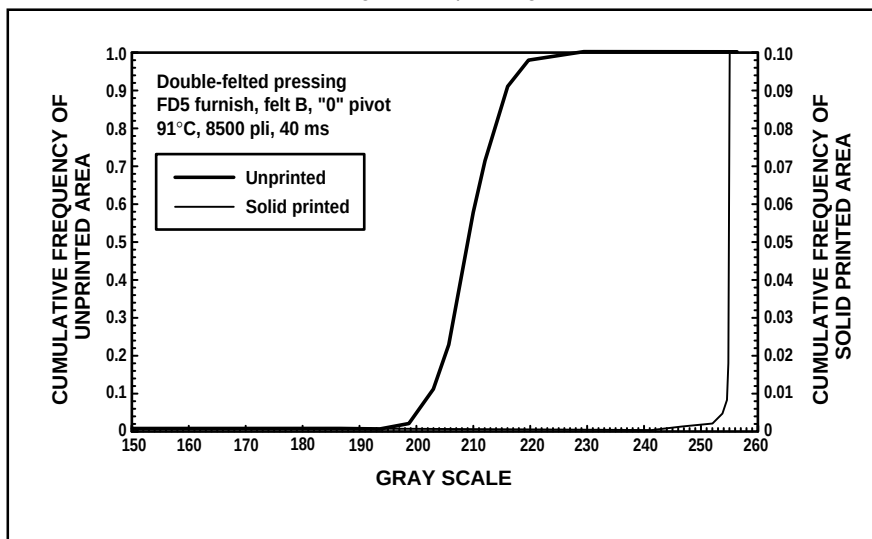
Double-ply and single-ply data were also consistent. This suggests that the hydrodynamic specific surface of the layer in contact with the heated platen controls delamination.

Outgoing solids for single-ply sheets made from high kappa number southern pine and OCC showed that impulse drying had a press dryness advantage over double-felted pressing for OCC content below 60% by weight. Outgoing solids for double-ply sheets showed that impulse drying was superior to double-

18. Cumulative frequency vs. gray scale for printed and unprinted regions of a single-ply 100% OCC sheet that underwent double-felted pressing



19. Cumulative frequency vs. gray scale for printed and unprinted regions of a single-ply 100% OCC sheet that underwent single-felted pressing



felted pressing and was independent of the top heated-ply freeness. For the case using the bottom, unheated ply made from 100% OCC at 600 mL CSF, impulse drying was superior when the top ply freeness was more than 600 mL CSF.

Many linerboard manufacturers use the cross direction (CD) STFI compression strength as the target strength parameter for adjusting their processes. Higher CD STFI index is therefore better. CD STFI index was reported as a function of

OCC content for single-ply sheets made from high kappa number southern pine and OCC. Impulse drying CD STFI index was superior to that of double-felted pressing provided OCC content was below 50%. Comparing the CD STFI index obtained by impulse drying to that of the control shows that impulse drying has a benefit over conventional papermaking independent of OCC content.

CD STFI index was also reported as a function of hot side freeness for

double-ply sheets. When the bottom ply was a blend of equal parts of high kappa number southern pine at 750 mL CSF and OCC at 600 mL CSF, impulse drying CD STFI index was superior to that of double-felted pressing with hot side freeness greater than 550 mL CSF. When the bottom ply was 100% OCC at 600 mL CSF, impulse drying CD STFI index was equal or superior for the entire range of hot side freeness. Impulse drying always resulted in superior strength compared to the control.

Objectives

Comparable experiments used the same pulp evaluated in laboratory simulation experiments on a sheet-fed pilot-scale shoe press (10). These experiments evaluated two roll coatings designated C and A. The following were the experimental objectives:

- Compare the performance of the C and A press roll surface coatings.
- Obtain process data over a wide range of linerboard sheet structures.
- Evaluate the resulting linerboard for important physical properties.

Laboratory-scale experiments had identified a methodology for structuring sheets for successful impulse drying. The design of the present experiments was to confirm the scale-up of that methodology to conditions more representative of commercial conditions. The single- and double-ply sheet structures used southern pine, Douglas-fir, and OCC pulps. This choice also covered a wide range of hydrodynamic specific surfaces.

Additional objectives of the present experiments were to compare impulse drying to double-felted hot pressing, single-felted hot pressing, and unpressed controls.

Results

The pilot experiments used an X2 pilot shoe press on a research laboratory paper machine at Beloit Corp., as **Fig. 1** shows. **Table I** shows the experimental conditions established to meet the stated objectives. These conditions represent the cases for each of the six furnishes covering a wide range of hydrodynamic specific surfaces.

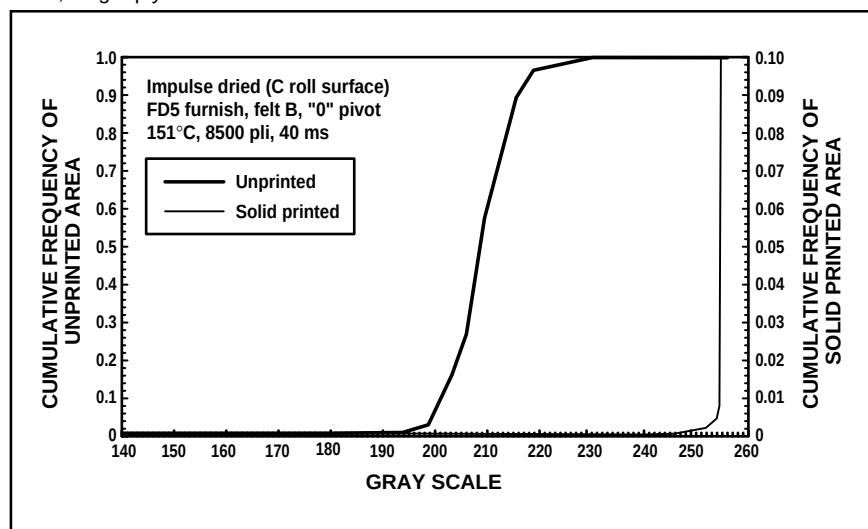
The pulp in these experiments came from the same batch used in conducting the laboratory-scale experiments (9). **Table II** shows the composition of the six furnishes under investigation. Furnishes with the prefix WF used a low-speed web former. Furnishes having an FD prefix used a Formette Dynamique at conditions similar to those used in the earlier work (9).

For each furnish, there was fiber analysis on samples of the prepared sheets. The results of the fiber identification are in **Table III**. **Table IV** summarizes the average fiber dimensions. The measured hydrodynamic specific surfaces for each furnish are in **Table V**.

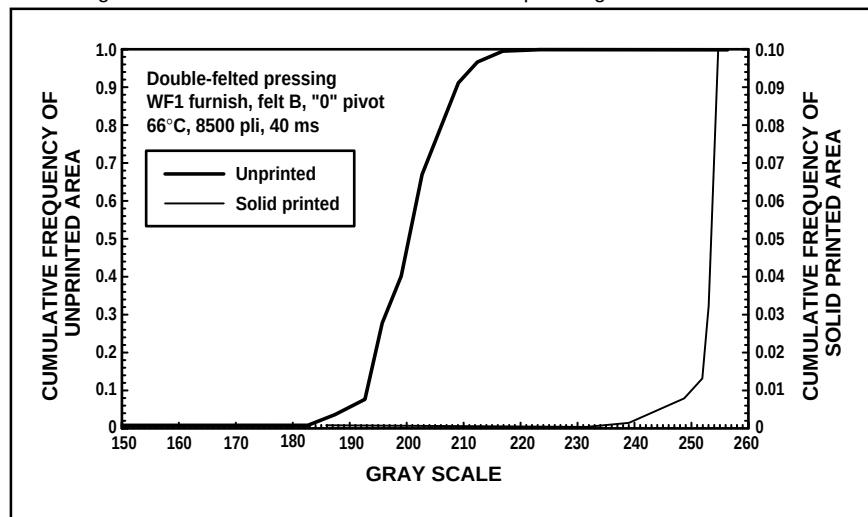
Critical temperatures for each impulse drying case came from ultrasound measurements and by visual observation. **Table VI** lists the critical temperatures and their uncertainties. The values are consistent with those previously measured in laboratory-scale simulations (9).

Figures 2–7 show outgoing solids as a function of furnish for each of the process variables. Note the arrangement of the furnishes in order of increasing hydrodynamic specific surface. In these and subsequent figures, the legend symbols identify the method of pressing used and the process case. For example, “D1” indicates that the data correspond to double-felted pressing at case 1 process conditions. Similarly, “C2” and “A2” correspond to impulse drying at case 2 process conditions using the C and A press roll surfaces, respectively.

20. Cumulative frequency vs. gray scale for printed and unprinted regions of an impulse dried, single-ply 100% OCC sheet



21. Cumulative frequency vs. gray scale for printed and unprinted regions of a single-ply 100% virgin kraft sheet that underwent double-felted pressing



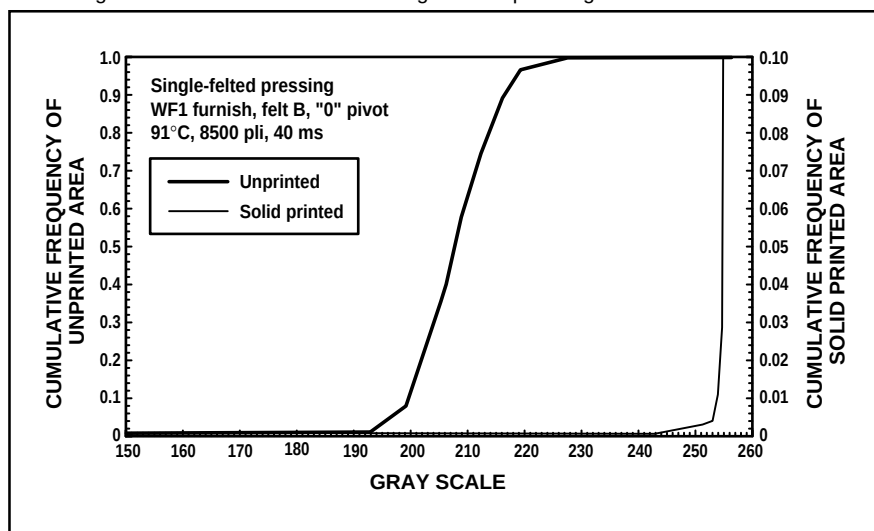
Impulse drying was always superior to double-felted pressing in achieving higher outgoing solids. There was also evidence that the A roll surface resulted in higher outgoing solids than the C surface.

Similarly, **Fig. 8** shows the effect of increasing the machine speed of the impulse dryer from 365 m/min (1200 ft/min) to 457 m/min (1500 ft/min). This reduces nip residence time from 40 milliseconds to 30 milliseconds. For the conditions investigated, the speed increase resulted in an outgoing solids reduction of

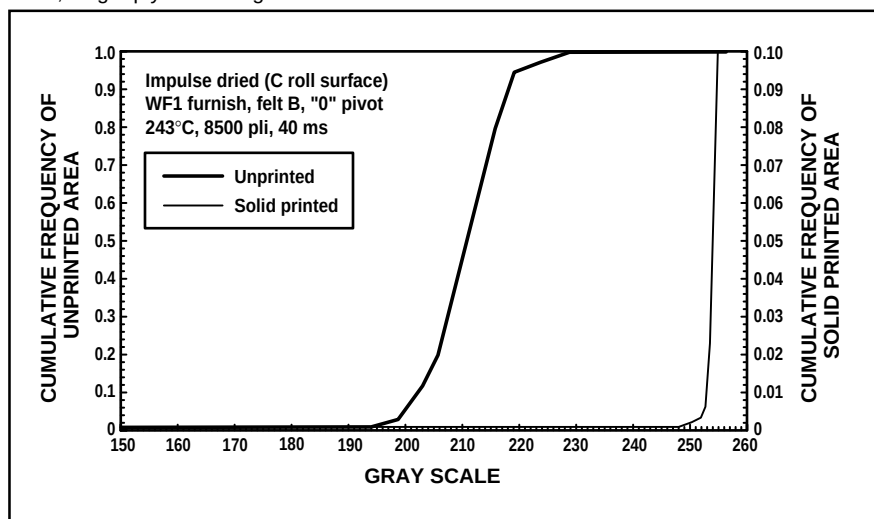
approximately 1%. Figure 8 also shows the effect of using “hard” felt wash water in place of deionized felt wash water. Using “hard” felt wash water tended to increase outgoing solids. One may speculate that longer postnip contact between the press roll and the sheet might have caused this. During this time, calcium carbonate might have accumulated on the roll surface.

Figures 9–14 show the geometric mean (GM) STFI indexes for case 1 through case 6. They compare double-felted pressing (D) to im-

22. Cumulative frequency vs. gray scale for printed and unprinted regions of a single-ply 100% virgin kraft sheet that underwent single-felted pressing



23. Cumulative frequency vs. gray scale for printed and unprinted regions of an impulse dried, single-ply 100% virgin kraft sheet



pulse drying with the C press roll (C) and to impulse drying with the A press roll (A). The STFI compression strength of impulse dried sheets tended to be higher or equal to that achieved by double-felted pressing. Differences due to press roll surface were not statistically significant.

There were also measurements of other important physical properties on double-felted pressed samples, single-felted pressed samples, and impulse dried samples at the critical temperature. These properties were Sheffield and Bendtsen roughness,

Gurley porosity, cracking angle, ink penetration, z-direction tensile, and burst.

Printing selected handsheets from the pilot shoe press experiment allowed evaluation for print quality. The sheets used the same printing conditions with an undiluted, black, flexographic ink. The printed image consisted of at least one solid black region for subsequent analysis of print mottle.

Image analysis evaluated the "unprinted" and "solid printed" areas of the sheet. Each area had a

determination of the normalized number of pixels having "gray scale readings" of 0 to 255. Here, a gray scale reading of 0 corresponds to white, and a gray scale reading of 255 corresponds to black. **Figures 15–23** show the cumulative distributions generated from the gray scale frequency distributions.

Figures 15–17 characterize the printed and unprinted areas of two-ply sheets composed of a 740 mL CSF freeness virgin kraft on the printed ply and an equipart blend of 740 mL CSF virgin kraft and 600 mL CSF OCC in the bottom ply. Figure 15 shows the double-felted pressed case. Figures 16 and 17 show single-felted pressed and impulse dried cases, respectively. The curves for the unprinted areas can quantify the contrast of the black ink to the unprinted sheet. The curves for the solid printed areas can quantify print mottle.

Figures 18–20 characterize the printed and unprinted areas of single-ply sheets composed of 450 mL CSF OCC. Figure 18 shows the double-felted pressed case. Figures 19 and 20 show single-felted pressed and impulse dried cases, respectively.

Figures 21–23 characterize the printed and unprinted areas of single-ply sheets composed of 740 mL CSF virgin kraft. Figure 21 shows the double-felted pressed case. Figures 22 and 23 show single-felted pressed and impulse dried cases, respectively.

Conclusions

There are many major conclusions that result from the pilot shoe press experiments:

- Press roll surface strength: The C roll coating was susceptible to chipping under shear, but the A roll did not chip.
- Critical impulse drying temperature: As in previous experiments (9), critical impulse drying tem-

Impulse Drying

perature depended on the hot side hydrodynamic specific surface. As expected, critical impulse drying temperature was higher for the “low thermal mass” C press roll than for the “higher thermal mass” A press roll. Interestingly, the choice of felt influenced the critical temperature.

- **Press dryness:** For a given set of pressing conditions, press dryness tended to decrease when the hydrodynamic specific surface of the sheet increased. In addition, press dryness resulting from impulse drying was generally higher than that achieved by double-felted pressing. Differences in dryness ranged from 8 percentage points for sheets having low hydrodynamic specific surface to 3 percentage points for less permeable sheets. The A roll yielded higher press dryness than the C roll, although it operated at lower temperature. Increasing the press load from 1050 kN/m (6000 lb/in.) to 1489 kN/m (8500 lb/in.) increased press dryness.
- **STFI compression strength:** The GM STFI compression strength of impulse dried sheets was consistently higher than that obtained by double-felted pressing. The difference in strength tended to be more significant for the more permeable sheet structures. For two-ply sheets, the STFI compression strength resulting from impulse drying was as much as 17% higher than that produced by double-felted pressing. There was no substantial strength difference when comparing sheets impulse dried with the two press rolls.
- **Felt water chemistry:** Using “hard” felt wash water tended to increase outgoing solids by approximately 3 percentage points. Water chemistry did not influence STFI index, however.
- **Speed effects:** Decreasing nip residence time had the expected result of decreasing water removal and STFI compression strength for all furnishes.
- **Gurley porosity:** For all furnishes, the impulse dried sheets were less porous than double-felted pressed sheets. In turn, these were less porous than the control sheets.
- **Ink penetration test:** Measurements of the rate of change of the contact angle for black flexographic ink drops on the felt side of the samples were independent of furnish and method of pressing. They were similar to measurements of commercial samples.
- **Sheet surface macro roughness:** Sheffield and Bendtsen roughness tests measured the macro roughness of the hot side of sheets. While the method of pressing and the extent of refining control surface macro roughness, the method of pressing was the dominant variable. Impulse dried samples were smoother than single-felted pressed samples. These were smoother than double-felted pressed samples.
- **Z-direction tensile:** The z-direction tensile strength is a measure of bond strength of plies. Impulse drying tended to increase significantly the z-direction tensile strength.
- **Burst index:** Impulse drying tended to increase burst strength compared to double-felted pressing.
- **Cracking angle:** Cracking angle depended on the level of refining of the fibers on the hot side of the sheet and the method of pressing. Refining was the dominant effect—excessive refining led to a low cracking angle. Impulse dried samples tended to have slightly lower cracking angles than double- or single-felted pressed sheets. Since impulse drying performs best when the heated ply is not heavily refined,

there should be no problem in achieving an acceptable cracking angle in commercial practice.

- **Print mottle:** Double-felted pressed sheets tended to have the worst print mottle. The print mottle exhibited by impulse dried sheets was equal to or better than that of the single-felted pressed sheets. Impulse drying darkened the sheet. Since an observer will primarily evaluate sheet quality on mottle rather than contrast, impulse drying will greatly affect print quality compared to double-felted pressing.

Future work

These shoe press experiments have set the stage for a renewed interest in attempting continuous, commercial speed, pilot-scale demonstration of impulse drying for linerboard. Impulse drying should proceed toward commercialization. In the meantime, there are still technical issues to resolve.

Shoe press experiments have demonstrated that the C ceramic roll coating is susceptible to shear failure when the roll operates at temperatures between 100°C and 150°C. Photomicrography of the failure zones confirms that these failures occurred when paper that had adhered to the roll was subjected to shear at the doctor blade. While the A roll is intrinsically stronger and did not experience failure, the issue of long-term durability for roll surfaces clearly requires further study. For this purpose, we have initiated an analytical modeling effort that will lead to the prediction of stress and temperature as a function of position and time in the various layers of a commercial impulse drying press roll.

With a grant from the Electric Power Research Institute, IPST has designed a modification to its existing pilot impulse dryer to allow it to function as a press roll durability test stand. The U.S. Department of

Energy has funded the construction, instrumentation, and operation of the durability test stand.

The heated roll will be driven at 762 m/min (2500 ft/min) and loaded against a felt saturated with water to provide a heat sink similar to that provided by paper in impulse drying. IR thermography will continuously monitor the roll surface to detect the onset of surface flaws in the coating. In addition, three-dimensional speckle interferometry will measure the state of strain on the roll surface. These surface strains with experimental stress-strain data will allow determination of surface stresses. It will then be possible to compare these experi-

mental surface stresses to the predictions of the finite element model. 

Literature cited

1. Crouse, J. W., Sprague, C. H., and Woo, J. D., *Tappi J.* 72(18): 211(1989).
2. Orloff, D. I., Kloth, G. R., and Rudemiller, G. R., *U.S. pat. 5,101,574* (April 7, 1992).
3. Orloff, D. I., *1989 Annual Meeting Proceedings*, AIChE, San Francisco, p. 156C.
4. Orloff, D. I., *J.P.P.S.* 18(1): J23(1992).
5. Orloff, D. I., *Yearly Report for Department of Energy Contract FG02-85CE40738, DOE/CE/40738-T6*, U.S. Dept. of Energy, Washington, 1991.
6. Orloff, D. I. and Lindsay, J. D., *TAPPI 1992 Papermakers Conference Proceedings*, TAPPI PRESS, Atlanta, p. 85.
7. Orloff, D. I. and Sobczynski, S. F., *Paper Technology* 34(10): 24(1993).

8. Orloff, D. I., Jones, G. L., and Phelan, P. M., in *Fundamentals of Heat Transfer in Porous Media* (M. Kaviany, Ed.) ASME, New York, 1992, Vol.193, pp. 141-150.
9. Orloff, D. I., *Tappi J.* 77(2): 169(1994).
10. Orloff, D. I., and Phelan, P. M., *Report #8 to U.S. Department of Energy Contract FG02-85CE40738, DOE/CE/40738-T8*, U.S. Dept. of Energy, Washington, 1993.

The U.S. Department of Energy, Office of Industrial Programs, supported this work through Grant No. DE-FG02-85CE40738 as did the member companies of the Institute of Paper Science and Technology and the Beloit Corp. The authors are grateful for their aid.

Received for review July 7, 1994.

Accepted July 20, 1994.

Presented at the TAPPI 1994 Engineering Conference.