Effects of basis weight and freeness on sheet permeability and critical impulse-drying temperature

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ABSTRACT: Delamination during impulse drying can be minimized by pressing sheets of low hydrodynamic specific surface area with a low-thermal-mass ceramic-coated surface. Critical temperature (T_c)*—the threshold before delamination occurs—is related to specific surface area. Heavier sheets have a higher specific surface because they retain more short fiber and fines than lightweight sheets, which contain macropores that facilitate fluid transport.* T_c *and outgoing dryness are highest for lightweight sheets produced at high freeness. Impulse drying provided superior dryness than double-felted extended-nip pressing for all tested combinations of basis weight and freeness. For sheets up to 205 g/m², compressive strength was higher for minimally refined impulse-dried sheets (740 mL CSF) than for more highly refined sheets (600 mL CSF) after extended-nip pressing.*

KEYWORDS: Basis weight, freeness, permeability, temperature, shock drying, linerboards.

Impulse drying is a high-intensity drying process first conceived by Wahren *(1)*. In his concept of the process, a wet web is pressed between an externally heated roll and a cold roll under high pressure for less than one second. A steam layer grows at the interface between the hot roll surface and the wet web, displacing water toward a felt at the surface of the opposing cold roll.

The key elements of impulse drying are high pressure (>3 MPa), high press-roll temperature (>100°C), and moderately long residence times (20–40 ms). Other high-intensity drying processes, such as press drying, utilize lower pressures and temperatures, with pressing times much greater than one second. While there are similarities among the high-intensity drying processes, impulse drying may be more viable because of its energy-efficient water removal and its short residence time, allowing for easy integration into a modern high-speed paper machine.

Impulse drying has the potential to provide significant energy savings *(2)*, especially in the dryer section. Impulse-dried sheets contain less water than conventionally pressed sheets, reducing the need for energy-intensive evaporative drying on steam-heated cylinders. This would be especially beneficial for dryer-restricted machines, where a reduced load to the dryer section would allow an increase in machine production. In addition, the greater strength of an impulse-dried sheet—derived from its greater density—should give mills the flexibility to use lower-quality and cheaper furnishes, such as recycled fiber, and/or to reduce refining energy *(2)*.

Despite these benefits, the development of impulse drying was slowed by the occurrence of sheet delamination at the nip exit *(3)*. While blistering was observed in early work *(4, 5)*, it did not draw serious concern. This is probably because the low-basis-weight sheets (45–90 g/m²) used in these early studies were thin enough to allow steam to escape easily without disrupting the network of bonded fibers.

The problem of sheet delamination became more apparent when impulse-drying experiments were run on sheets with basis weights of 100–440 g/m²

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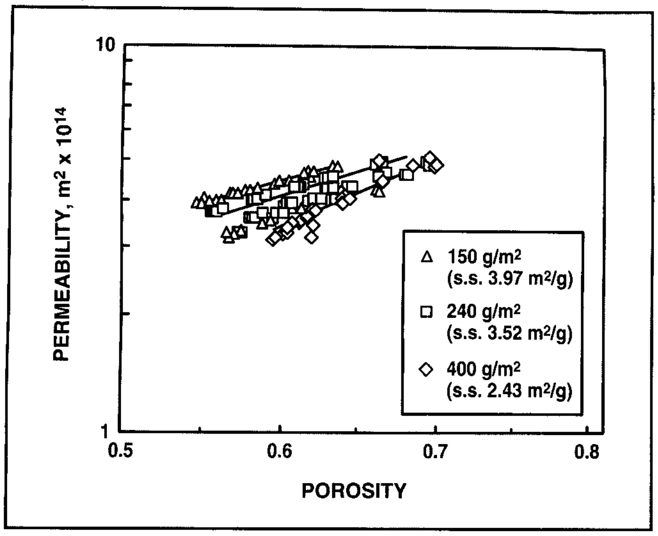
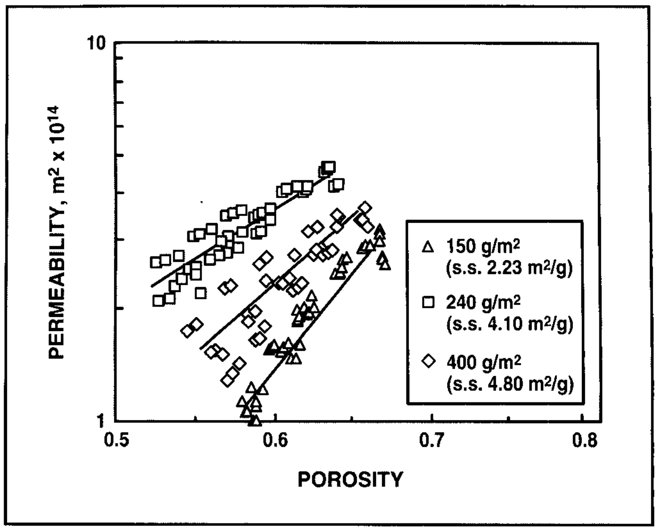
1. Permeability as a function of porosity for sheets formed at three basis weights from pulp at 740 mL CSF (s.s. represents specific surface)



2. Permeability as a function of porosity for sheets formed at three basis weights from pulp at 600 mL CSF (s.s. represents specific surface)



made from furnishes of freeness below 600 mL CSF. Delamination of these higher-basis-weight sheets occurred at low heated-roll temperatures that were similar to those used in hot pressing *(3)*. Hence, there was no perceived benefit for impulse drying over traditional hot pressing. While several factors were suspected to contribute to delamination, the exact mechanism was not known.

The delamination problem was overcome by developing a low-thermal-mass coating for the heated press surface *(6–8)*. A low-thermal-mass pressing surface reduces the quantity of heat conducted to the sheet during the pressing event. This results in lower post-press sheet temperatures and, hence, less steam flashing at the nip exit. Additional research also showed that sheets of greater permeability could be manufactured by manipulating fiber and network properties such as basis weight, ingoing solids, and degree of refining *(9)*. The enhanced permeability of such sheets facilitates the escape of flashed vapor in the sheet during the drying event, thus reducing the likelihood of delamination.

This report demonstrates that a low-thermal-mass ceramic-coated press surface can be used to impulse dry linerboard grades up to 400 g/m² without inducing sheet delamination, even at 600 mL CSF. Measurements of Darcian permeability show that by comparing the hydrodynamic specific surface of paper webs, it is possible to predict the upper limit of roll temperature that can be used to impulse dry a sheet without inducing delamination.

This report also presents the results of tests comparing the performance of impulse drying and double-felted extended-nip pressing. Both processes were performed at the same press impulse, and performance was measured in terms of post-press dryness and sheet compression strength.

I. Mean fiber dimensions

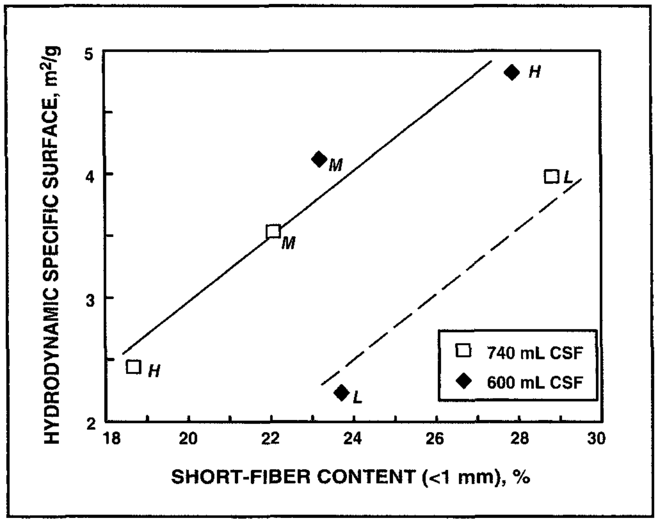
Pulp freeness, mL CSF	*Basis weight, g/m²*	*Fiber coarseness, mg/100 m*	*Fiber width, µm*	*Fiber perimeter, µm*	*Weight-weighted fiber length, mm*	*Short-fiber content (<1 mm), %*
600	150	30.8	36.8	85.6	3.10	23.72
600	240	31.2	31.5	75.8	2.99	23.21
600	400	34.0	34.1	81.4	2.76	27.92
740	150	31.0	32.6	77.6	3.75	28.82
740	240	33.6	32.4	78.0	3.56	22.10
740	400	33.4	34.8	84.4	3.62	18.71

Experimental design

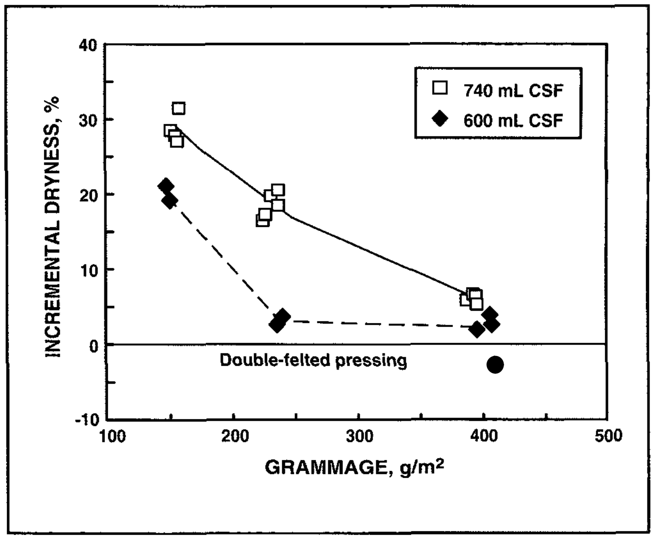
The objective was to determine the critical temperature (T_c)—the maximum platen temperature that can be used to impulse dry a sheet without inducing delamination—over a range of basis weights and freenesses for sheets impulse-dried with a ceramic pressing surface. Three basis weights (150 g/m², 240 g/m², 400 g/m²) and two levels of pulp freeness (600 mL CSF, 740 mL CSF) were used in this study. The range of freeness was chosen to typify that used in linerboard mills.

Impulse drying was accomplished on a lab-scale MTS press and operated in the same manner as performed by Orloff and Lindsay *(9)*. Specific conditions for these experiments include:

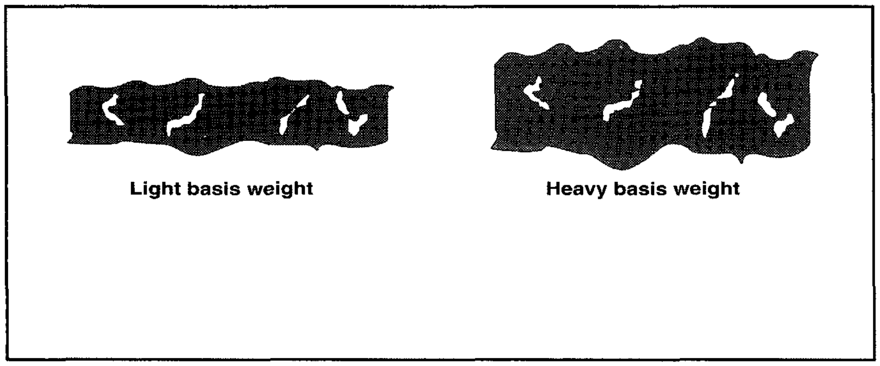
3. Hydrodynamic specific surface as a function of short-fiber content (<1 mm) for sheets formed at three basis weights and two levels of freeness



5. Incremental dryness for impulse-dried (at T_c) sheets as a function of grammage at two levels of freeness



4. Placement of macropores in a lightweight sheet and a heavyweight sheet of greater caliper



- Sheets preheated to 85°C
- Extended-nip press-pulse shape
- Impulse of 0.23 MPa·s
- Nip residence time of 40 ms.

All sheets were impulse dried from 49% solids, since an impulse-drying system probably would be placed after a third press *(10)*. Maximum water removal at T_c was determined for impulse-dried sheets and compared with simulated double-felted extended-nip pressing at the same impulse.

Permeability was measured in an effort to characterize the sheet internal structure (flow channels) as an indicator of impulse-drying performance in future pilot-scale trials. Permeability was measured using the apparatus developed by Lindsay and Brady *(11)*. Saturated sheets were compressed to a known pressure, and sheet porosity was determined based on caliper. Flow through the sheet was then measured to determine the permeability at that porosity. Compression pressure on the saturated sheets was systematically increased to obtain a graph of permeability vs. porosity. Permeability was calculated from Darcy's law and the Kozeny–Carman equations. This, together with sheet solids at known pressures, permits calculation of hydrodynamic specific surface and volume.

Fiber length distributions also were measured in an effort to establish a correlation with hydrodynamic specific surface. STFI index was measured to compare the performance of impulse drying and double-felted extended-nip pressing in terms of sheet density and strength development.

Results

Permeability

Sheet permeability was determined prior to impulse drying. Experiments have shown that post-press permeability does not vary significantly from permeability before impulse drying *(12)*. Therefore, permeability measured before impulse drying is the reported result. **Figures 1 and 2** present permeability as a function of porosity for sheets produced at the three basis weights from furnishes of 740 mL CSF and 600 mL CSF, respectively.

As seen in Fig. 1, hydrodynamic specific surface (as measured by permeability) for the sheets at 740 mL CSF was nearly independent of basis weight. There is only a slight difference between the permeabilities of the lightweight and heavyweight sheets. Figure 2, on the other hand, shows that the more heavily refined pulp of 600 mL CSF produced sheets with lower permeability (and thus higher specific surface), indicating the detrimental effect of increased refining.

Permeability for the sheets produced at 600 mL CSF is dependent on basis weight, in contrast to the sheets produced at 740 mL CSF. It is well established that refining causes both fiber fibrillation and cutting. Both increase the fiber surface area, especially fines, which are colloidal in nature.

Next, we attempted to correlate hydrodynamic specific surface to fiber characteristics. Weight-weighted average fiber length and cell-wall width were measured, while coarseness and perimeter were calculated from the results. **Table I** shows the mean fiber dimensions for the six sheets.

No significant variation was found in cell-wall thickness, coarseness, or perimeter. This was expected, since the furnish did not change, only the degree of refining. However, we observed a trend of decreasing fiber length with increasing basis weight. It seems that higher-weight sheets contained more short fiber. Fiber length was measured under a microscope, so it was not possible to measure the fines, which were too small. The differences in fiber length for the six sheets are accurate and reflect the average length in the sheet. The results in Table I indicate that refining indeed shortened fiber length, as reflected in the shorter average length of the sheets prepared at 600 mL CSF compared with those prepared at 740 mL CSF.

II. Sheet properties

Pulp freeness, mL CSF	*Basis weight, g/m²*	*Specific surface area, m²/g*	T_c, *°C*	*Sheet density, g/m³*	*Specific elastic modulus at* T_c, *MN·m/kg*
		Impulse dried at T_c			
600	150	2.23	351	0.878	0.2126
600	240	4.10	251	0.820	0.2170
600	400	4.80	241	0.779	0.1768
740	150	3.97	497	0.860	0.2050
740	240	3.52	497	0.836	0.2232
740	400	2.43	375	0.794	0.1706
		Double-felted pressed			
600	150	2.23	...	0.755	...
600	240	4.10	...	0.813	...
600	400	4.80	...	0.775	...
740	150	3.97	...	0.702	...
740	240	3.52	...	0.754	...
740	400	2.43	...	0.767	...

Macropores

Figure 3 shows the correlation between the calculated value of hydrodynamic specific surface and the short-fiber content (percent <1 mm). In this plot, *H* represents the heavyweight sheets (400 g/m²), *M* represents the medium-weight sheets (240 g/m²), and *L* represents the lightweight sheets (150 g/m²). The 240-g/m² and 400-g/m² sheets fall along one line, while the 150-g/m² sheets fall along a line below the heavier basis weights. This is interpreted as evidence for the presence of macropores, as postulated by Lindsay *(11)*. The thin 150-g/m² sheets have a permeability that is controlled by macropores. At a given short-fiber content, the 150-g/m² sheets possess a lower specific surface than the heavier 240-g/m² and 400-g/m² sheets. We interpret this to mean that there is a basis-weight threshold beyond which macropores no longer pass through the sheet thickness to provide a quick mode of fluid transport.

Macropores are postulated to be boundaries between fiber aggregates that pass through the entire *z*-direction of a low-caliper, low-basis-weight sheet. As sheet weight increases, however, the macropores are averaged out, and the sheet permeability becomes dictated by the specific surface development of the fibers within the sheet. **Figure 4** shows how macropores are thought to be represented in a sheet of two different basis weights. As basis weight increases, caliper increases, and the macropores are averaged out. Because the macropores no longer traverse the entire sheet caliper, permeability is controlled by the hydrodynamic specific surface of the fines and fibers in the sheet.

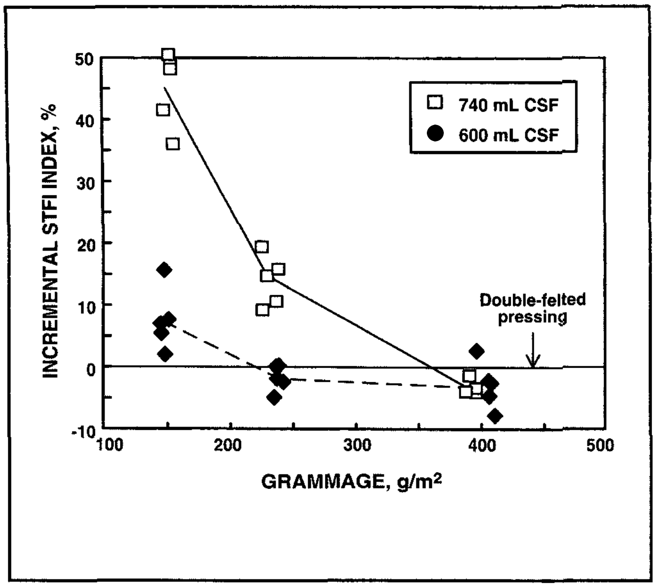
Macropores are not yet a fully accepted or understood explanation of the increased permeability of lightweight sheets, but a reasonable one. In any event, the permeability—whether controlled by fiber length and fibrillation or macropores—is a good predictor of impulse-drying T_c.

Impulse drying vs. double-felted pressing

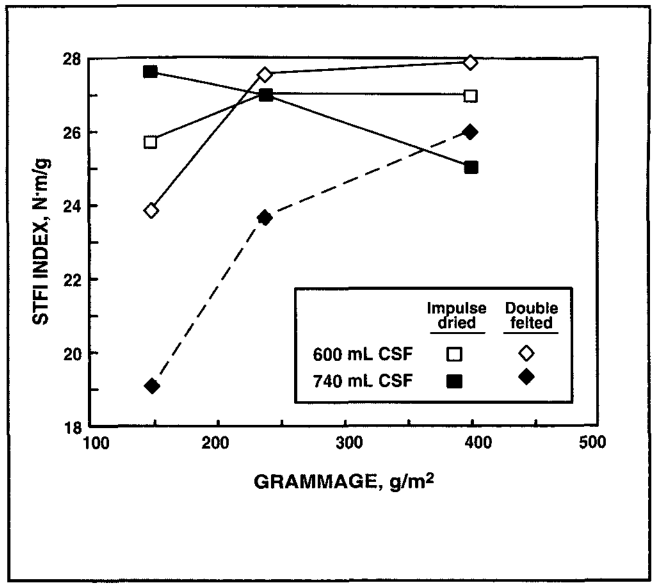
Dryness. Impulse-dried sheets were compared with double-felted, extended-nip-pressed sheets. Impulse drying achieved greater post-press dryness over all sheet weights at both freenesses. The plot of percent incremental dryness in **Fig. 5** shows the percentage improvement of impulse drying at T_c over double-felted pressing. Incremental dryness is defined as the difference in percentage dryness between an impulse-dried sheet and that of a similar sheet after double-felted extended-nip pressing.

Incremental sheet dryness reveals that higher-freeness, lower-weight sheets achieve the greatest degree of dryness. This is because the higher-freeness, lower-weight sheets possess the highest permeability, while heavier basis-weight sheets contain more water. A heavier sheet with more water will not achieve the same degree of dryness because the steam is unable to propagate into the sheet very far.

6. Incremental STFI index for impulse-dried (at T_c) sheets as a function of grammage at two levels of freeness



7. Average STFI index as a function of grammage for impulse-dried (at T_c) and pressed sheets at two levels of freeness



On the other hand, the presence of macropores in the lightweight sheets provides quick passage of steam through the sheets produced at 600 mL CSF and 740 mL CSF. As sheet weight increases, permeability decreases, and the flow of liquid from the sheet decreases for both freeness levels. Water is unable to freely flow through the sheet as the permeability decreases and hydrodynamic specific surface increases.

There is a limit, however, to the platen temperature that can be used in impulse drying. This limit, T_c, is the highest temperature that can be used to impulse-dry a sheet without inducing delamination. The T_c for impulse drying is determined from a calculation based on specific elastic modulus as measured with an ultrasonic tester *(6)*. A sudden increase in the percent coefficient of variation of the specific elastic modulus indicates sheet delamination. This determination is then compared with the observation of sheet blistering during experimentation. A good correlation exists between observed delamination and the laboratory determination. The T_c was highest for the 150-g/m² sheets produced at 740 mL CSF. The higher the permeability, the greater is the post-press dryness that can be achieved. **Table II** presents the T_c determined for each case.

Sheet density. The density of impulse-dried sheets tends to increase with increasing platen temperature. Previous work by Orloff *(13)* showed that the density improvement is due to the combined effect of mechanical pressing load and the enhanced compressibility of the fiber mat with increasing platen temperature. For the sheets produced at 740 mL CSF, the impulse-dried 150-g/m² sheets showed the greatest density improvement compared with double-felted-pressed sheets. Impulse drying also improved density for the higher-weight sheets over that of double-felted pressing, but to a lesser degree. Little density improvement was observed for impulse-dried sheets at 600 mL CSF. The double-felted sheets were approximately the same density as the impulse-dried sheets, with the exception of the 150-g/m² sheets, where a slight improvement was observed with impulse drying. The lack of density development for sheets produced at 600 mL CSF is attributed to the lower platen temperatures required to accommodate the lower permeability of the sheets produced from the more highly refined pulp.

Figure 6 shows the incremental STFI index (compression strength) for impulse-dried sheets compared with double-felted pressing. Sheets produced at both levels of freeness exhibit a decrease in incremental STFI index as the basis weight increases. STFI index for the impulse-dried sheets produced at 600 mL CSF is slightly lower than that of double-felted sheets, with the exception of the 150-g/m² sheets, which had slightly higher STFI index. The greater STFI increment observed for the sheets produced at 740 mL CSF is attributed to the greater permeability of these sheets, permitting a higher impulse-drying T_c that produces superior density.

Figure 7 shows STFI index of double-felted-pressed sheets and impulse-dried sheets for both freenesses and all three basis weights. From this plot, it is apparent that, for sheets produced at 740 mL CSF, impulse drying provides a strength advantage up to a basis weight of 240 g/m². The higher permeability afforded by the high freeness allows higher platen temperatures and subsequent sheet density and strength. Thus impulse-dried sheets produced from minimally refined pulp (740 mL CSF) are stronger than double-felted extended-nip-pressed sheets produced from more highly refined pulp (600 mL CSF) up to a basis weight of 205 g/m^2, the most common linerboard sheet manufactured. In this case, energy would be saved by the lower fiber-refining requirement.

Conclusions

The use of low-thermal-mass ceramic coatings on impulse-drying rolls inhibits the occurrence of delamination for heavyweight grades. With a ceramic-coated roll, impulse drying provided higher post-press sheet dryness than double-felted pressing for sheets produced at 600 mL CSF and 740 mL CSF. Impulse drying was most effective on sheets produced at 740 mL CSF, which had higher dryness and STFI index than sheets produced at 600 mL CSF. Impulse-dried sheets produced from minimally refined pulp (740 mL CSF) were stronger than double-felted extended-nip-pressed sheets produced from more highly refined pulp (600 mL CSF) up to a basis weight of 205 g/m^2.

Laboratory investigation of sheet permeability suggests that lightweight sheets (150 g/m^2) contain macropores that contribute to sheet permeability. At some unidentified higher sheet weight, macropores no longer play a role in sheet permeability, and permeability is governed by the degree of fiber fibrillation and fiber cutting that occur during refining. Sheets of greater permeability achieve the highest dryness values at a given basis weight. TJ

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