

Discussion of impulse drying physics: comments on E. L. Back's "Why is press drying/impulse drying delayed?"

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In the March 1991 issue of *Tappi Journal*, E. L. Back presents a critical review of impulse drying (1). His comments on the roles of thermal softening and viscosity reduction emphasize relevant areas that perhaps have not received enough attention in past work on impulse drying. There is a need, however, to respond to his views of impulse drying physics, which challenge the theories proposed in several past studies (2-9).

In Back's view, vapor formation cannot play a role in liquid water removal. Impulse drying is said to be a combination of "superhot wet pressing" and some evaporative drying. The feature of intense heat transfer is played down, and impulse drying heat transfer is said to be comparable to hot pressing or even convective drying as found in Yankee dryers.

Unfortunately, Back's discussion of impulse drying heat flux is affected by a typographical error in one publication and possibly by a misreading of data in another. Furthermore, the analysis of vapor pressure in impulse drying is inconsistent with the principles of thermodynamics.

The issue of heat flux

The intense heat transfer applied in impulse drying has been advanced as a feature which distinguishes it from other conventional pressing and dry-

ing processes. Sprague, for example, offers a paradigm for comparing water removal processes on a plot of process temperature versus energy demand per mass of water removed (10). Such a comparison suggests that impulse drying lies in a unique regime, with an exceedingly high operating temperature (much greater than found in hot pressing) and with a relatively low energy demand. The heat transfer mechanism is then of pivotal importance in discussing impulse drying as a novel technology.

Back claims that the heat flux in impulse drying is not unusual for paper drying processes. Unfortunately, a misreading of data in one publication, combined with an unfortunate typographical error in another, led to this conclusion. From our numerical modeling of an idealized impulse drying process (7), Back cites a peak heat flux value of 0.8 kW/m² and compares it to a value of 0.08 MW/m² from press drying. However, the numerical results in the cited publication clearly show peak fluxes on the order of 5 MW/m² (5000 kW/m²), not 0.8 kW/m². Back also compares data from Sprague (10) to Yankee dryer data, finding the impulse drying fluxes to be of the same order [Fig. 16(1)]. Unfortunately, the graph from Sprague suffers from an obvious typographical error in the axis labeling, with unreasonable values as high as 400,000 kW/m² listed.

Back realized that an error was made, but the "corrected" labeling in the reproduced figure still shows peak heat flux values that are an order of

magnitude below the values commonly cited elsewhere in the literature (5-7, 9). Typical measured values of peak heat flux range from about 2 MW/m² to 8 MW/m². Such values are much beyond those reported for press dryers (0.08 MW/m²) or Yankee dryers (<0.15 MW/m²). Impulse drying can be distinguished from most other pressing and drying processes by the brief but intense heat transfer that occurs as a wet sheet is pressed against a hot roll (about 300°C). The heat flux behavior of impulse drying thus distinguishes it from other processes.

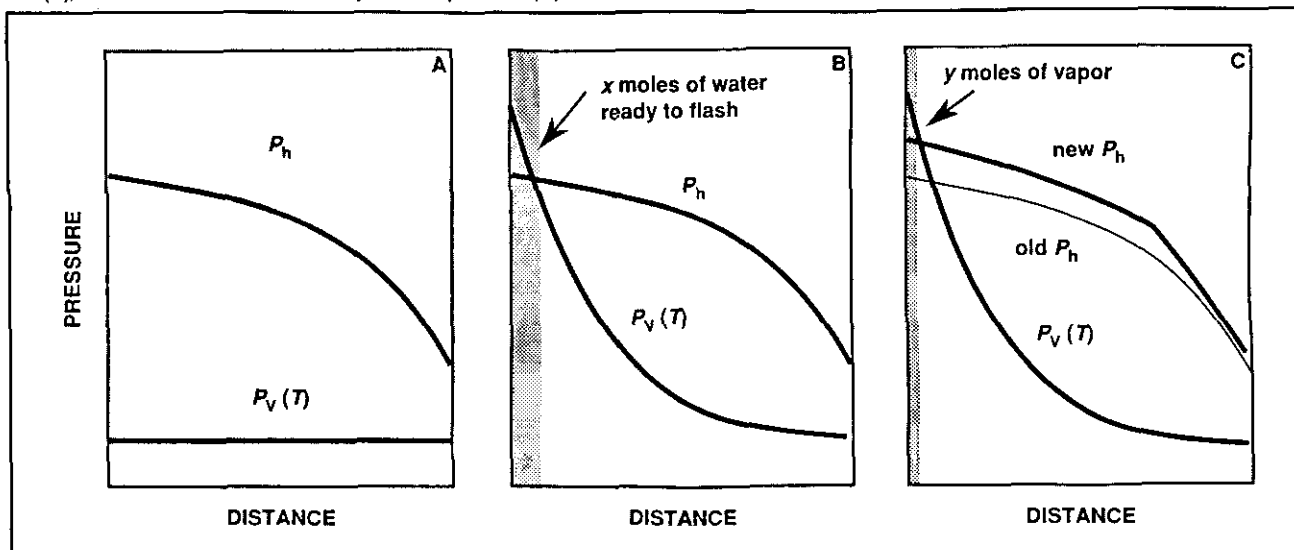
Hydrodynamic pressure: the effect of a vapor phase

Several studies at IPST have indicated that phase-change heat transfer plays a role in impulse drying (4-6, 11). While viscosity reduction and thermal softening of fibers may be important factors in water removal, the formation of a pressurized steam zone at some point in the nip has received attention as a mechanism which can displace additional liquid water, or at least resist rewet, in impulse drying (7).

Back, however, claims that the formation of a vapor phase cannot increase water removal. If it forms, Back argues, it simply "replaces" the water that was there, staying at equilibrium with the water pressure that was there or in the adjacent layer in the sheet, unable to act separately

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1. Hydraulic and vapor pressures at an instant in a room-temperature sheet pressed with a cool platen (A), after an instantaneous temperature rise (B), and with the sheet at thermodynamic equilibrium (C). The distance is measured from the top of the sheet.



on the liquid water [pp. 142 and 143 (1)]. In other words, the vapor phase cannot increase the hydraulic pressure gradient across the sheet and thus cannot help move liquid water out of the web.

Unfortunately, Back's argument is not thermodynamically correct. True, the vapor phase must be in equilibrium with whatever liquid it contacts; so, neglecting the secondary effect of capillary pressure, the vapor and liquid phases must be at the same pressure where they share a boundary. However, as heat is added to the system, water and steam can reach a new equilibrium at a higher pressure and temperature. (This is what happens in a typical pressure cooker.)

When heat is added to liquid, vapor can form when $T > T_{eq}(P)$, where T is the local temperature in the sheet and T_{eq} is the saturation temperature at a pressure P . Vaporization increases the number of moles in the gas phase, and if the space for expansion is limited (by the presence of a solid roll, for example), the gas phase pressure will increase according to the gas law, $P = nRT/V$. The increase in gas pressure results in a new equilibrium condition with gas and liquid at a higher pressure than before. (However, the hydraulic pressure may not exceed the total applied pressure, so heat transfer will not affect the hydraulic pressure in the early portion of a strongly flow-controlled nip. If the vapor pressure exceeds the applied pressure, "lift off"

and steam venting could occur.)

Consider a sheet of paper undergoing pressing with a cool metal platen. The hydraulic pressure at a given time may resemble that sketched in Fig. 1, Frame A. If the water in the sheet is at room temperature, the vapor pressure of the liquid, P_v , will be well below the actual hydraulic pressure, P_h .

Now suppose the platen and the upper layers of the sheet were instantly heated to give a vapor pressure curve like that shown in Frame B. Some of the liquid (x moles) is superheated ($P_v(T) > P_h$, or $T > T_{eq}(P_h)$), so it is ready to flash. But as flashing proceeds, the gas phase pressure rises rapidly, which in turn increases the liquid pressure and leads to a new equilibrium state. Under this new equilibrium, y moles have vaporized, with $y < x$, as shown in Frame C.

The important effect is that heat transfer and equilibrium considerations lead to a new hydraulic pressure gradient in the liquid, which can increase the rate of liquid flow out of the sheet. Such systems, with idealized physical properties, have been numerically analyzed (7, 12).

Proposed pressure gradients sketched in Fig. 15 of Back's article are also thermodynamically improper. In this figure, Back speculates on the distribution of hydraulic and network pressures across a sheet during pressing with cold and hot surfaces. The sketches show a dry, steam-filled zone at a hydraulic pres-

sure substantially lower than that in the middle of the sheet. I can conceive of no scenario in which heating a pressing surface could lead to a fluid pressure distribution as Back has sketched, with a high hydraulic pressure in the middle of the sheet and a lower hydraulic pressure at the pressing surface. Instead, the fluid pressure in a nonexpanding nip should be highest at the pressing surface and should drop continuously toward the felt, whether the fluid is steam or liquid water.

The solid network takes up more of the total pressure, according to the caption of Back's figure, because "the compressed network can withstand a higher pressure." It is true that the heating of the web next to the hot surface causes a softening of the fibers and increases the densification of the solid, but this does not mean that the fibers take up more of the load. (In fact, softening may lead to more of the load being taken up by the fluid as the sheet compresses and the hydraulic pressure rises.) The pressure actually taken up by the fibers, P_f , in any layer of the sheet, is determined by the difference between the applied pressure, P_{app} , and the local hydraulic pressure, P_h :

$$P_f = P_{app} - P_h \quad (1)$$

The local hydraulic pressure in a dynamic system is affected by many

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things, including equilibrium considerations if vapor is present. Nevertheless, Eq. 1 should be true whether the fluid at a particular point is gas or liquid. A vapor at P_h exerts just as much force as a liquid at that pressure.

While a pressurized vapor zone can enhance the hydraulic pressure gradient in water and thus assist water removal and resist rewet, it is not clear how significant this effect is. Even if vapor zones are important, most of the water removal occurs through standard pressing mechanisms, and separating the effects of vapor action from fiber softening, viscosity reduction, and evaporation is difficult. Experimental evidence with flash X-ray radiography indicates that vapor can displace liquid water in impulse drying (8), but this study left many questions unanswered.

Back cites Macklem and Pulkowski (13) for evidence that vapor plays no role in water removal. Their study, however, does not present a proper assessment of the issue. For example, the authors claim that steam formation would instantly displace the unbound water, resulting in sheets with 70% dryness. Since 70% dryness is usually not observed, they rule out steam formation. The analysis completely overlooks the significant effect of viscous resistance in a compressed sheet. [See my recent presentation at the 1991 Pira Conference for a discussion of displacement processes (14).] Back also claims that a vapor pressure effect in impulse drying is contradicted by data showing improved water removal with higher mechanical pressures. This does not follow, however. Increased compression of a sheet almost always increases water removal. Indeed, the proposed physical model of impulse drying predicts that higher vapor pressures should occur in a higher pressure nip, although it may take longer for the hydraulic pressure to drop enough for vapor to form.

While further work is needed to quantify the significance of vapor displacement in impulse drying, one piece of evidence clearly indicates that vapor formation is important: sheet delamination. If post-nip vapor pressures in the sheet can be great enough to delaminate the sheet, vapor pressures in the nip should also be available to assist water removal or at least

to resist rewet as the sheet begins to expand.

Summary

Back's contributions to water removal processes have been substantial, and the information he presents about press drying and other technologies raises several valid points and challenges with respect to impulse drying. However, his elimination of vapor displacement as a potential dewatering mechanism, whether for impulse drying or for direct displacement dewatering (14), is unfounded. Likewise, the claim that no new mechanisms are involved in impulse drying cannot be substantiated by an appeal to heat flux data.

This is not to say that vapor displacement is proven to be significant nor to say that impulse drying is dominated by any new mechanisms. But the intense phase-change heat transfer that occurs, coupled with the possibility of vapor action in removing liquid water, makes impulse drying a truly interesting process that cannot justifiably be treated as just another variant of press drying, hot pressing, wet pressing, or tissue drying. □

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