Flash X-ray visualization of multiphase flow during impulse drying

J. C. Zavaglia and J. D. Lindsay

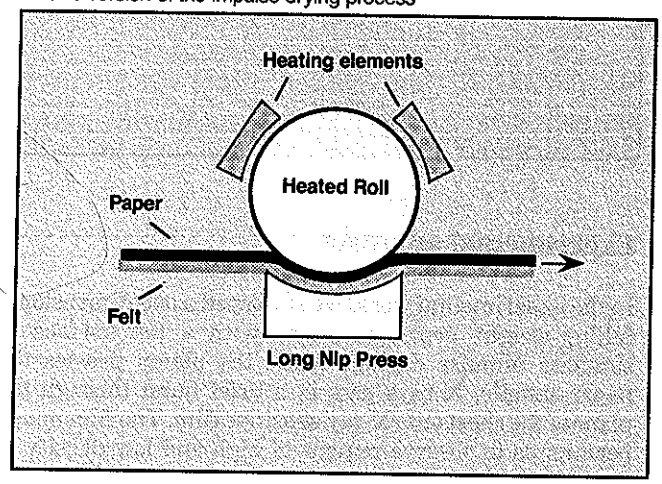
Flash X-ray radiography helps us to visualize processes inside a sheet and felt combination during impulse drying, allowing us to capture rapid, transient events that occur in a 30-ns timeframe.

Impulse drying is a new technology based on research at The Institute of Paper Science and Technology (IPSAT). It is a process in which water is removed from a moist paper web as it passes through a long nip press with one intensely heated roll (**Fig. 1**). Impulse drying typically uses applied pressures of 3–6 MPa, temperatures of 250–350°C, and nip residence times of 15–100 ms. This process offers the potential for high levels of dryness at lower energy and capital costs than is possible with conventional pressing and drying.

The physical aspects of impulse drying have been studied by several researchers (*1–4*). Based on heat flux, temperature, and sheet deformation measurements, these researchers proposed a vapor displacement mechanism. When a hot roll comes in contact with a moist web, high-pressure steam is generated in the surface of the sheet next to the hot roll. This steam will displace liquid water from the sheet into the felt.

Recently, computational techniques have been applied to impulse drying to examine the role of heat transfer and fluid flow in an idealized impulse-drying-like process (*5*). The predictions point to the importance of internal vapor generation in the water removal process and show that a heat-pipe mechanism may occur in impulse drying, with sustained evaporation and boiling near the hot surface and with condensation in cooler regions of the sheet. Dreshfield (*6*) demonstrated a related mechanism in conventional cylinder drying by tracking the migration of water-soluble dye. Numerical predictions also show that most of the displacement occurs as a two-phase zone displaces a saturated zone; a dry zone near the hot surface undergoes much slower growth (*5*).

1. One version of the impulse drying process



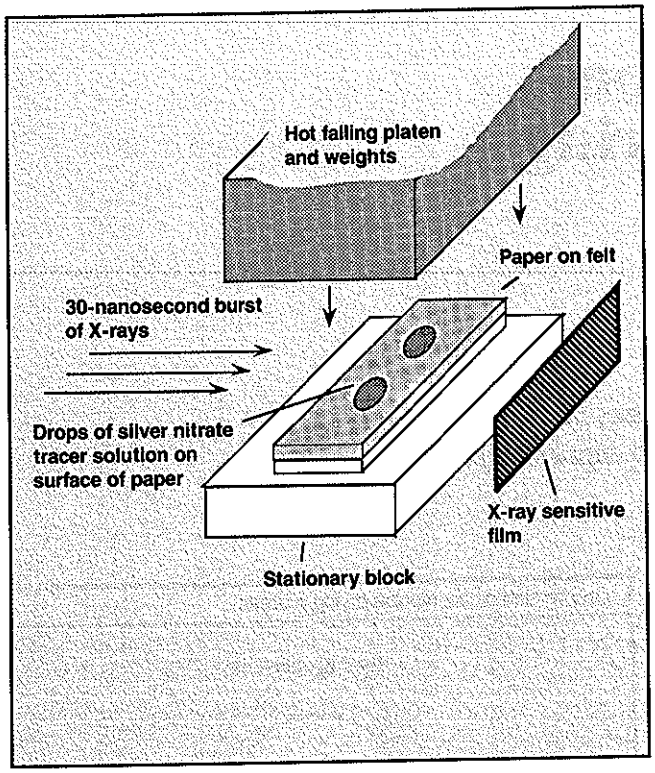
The role of the vapor zone, or even its existence, is still not certain. No direct observation of its presence has been possible in the past, and the numerical predictions of its role can be challenged because of limiting simplifications in the model. Indeed, some researchers have hypothesized that vapor does not form or that it plays no significant role during impulse drying (*7*). The formation of at least some vapor, however, seems mandated by thermodynamics, for the only way to keep water in a liquid state next to a surface with a temperature of, say, 300°C would be to maintain a hydraulic pressure of over 8.5 MPa (1200 psi) during the entire nip of an impulse drying event—an impossibility.

Our objective in this study was to develop a method to directly observe vapor and liquid in a sheet during impulse drying to gain more understanding about the role of the postulated vapor zone.

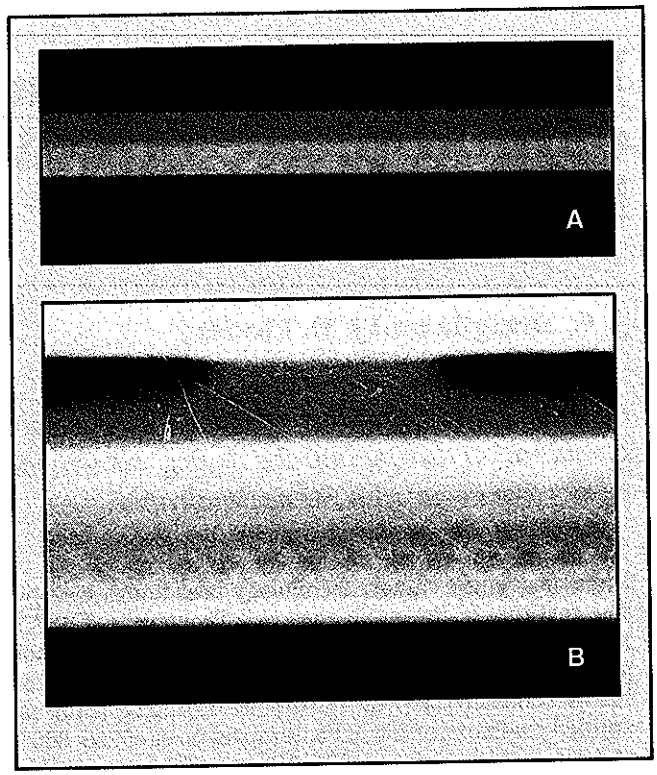
Zavaglia is a graduate student, and Lindsay is an assistant professor at The Institute of Paper Chemistry*, Appleton, Wis. 54915.

*The Institute of Paper Chemistry has changed its name to The Institute of Paper Science and Technology (IPSAT) and has relocated to Atlanta, Ga.

2. Detail of falling-weight press simulator, showing the horizontal path of X-ray flash through paper and felt



3. Radiographs of linerboard sheets on Nomex felts (A) during pressing and (B) before pressing



Experimental approach

In the experimental work, we employed a one-dimensional falling-weight press simulator with a hot surface to simulate impulse drying. While the platen presses the paper sample, X rays pass in a brief burst through the plane of the sheet onto X-ray-sensitive film. The film image permits us to observe regions of high and low density in the sheet, which represent liquid and vapor. **Figure 2** illustrates the basic design.

The flash X-ray technique

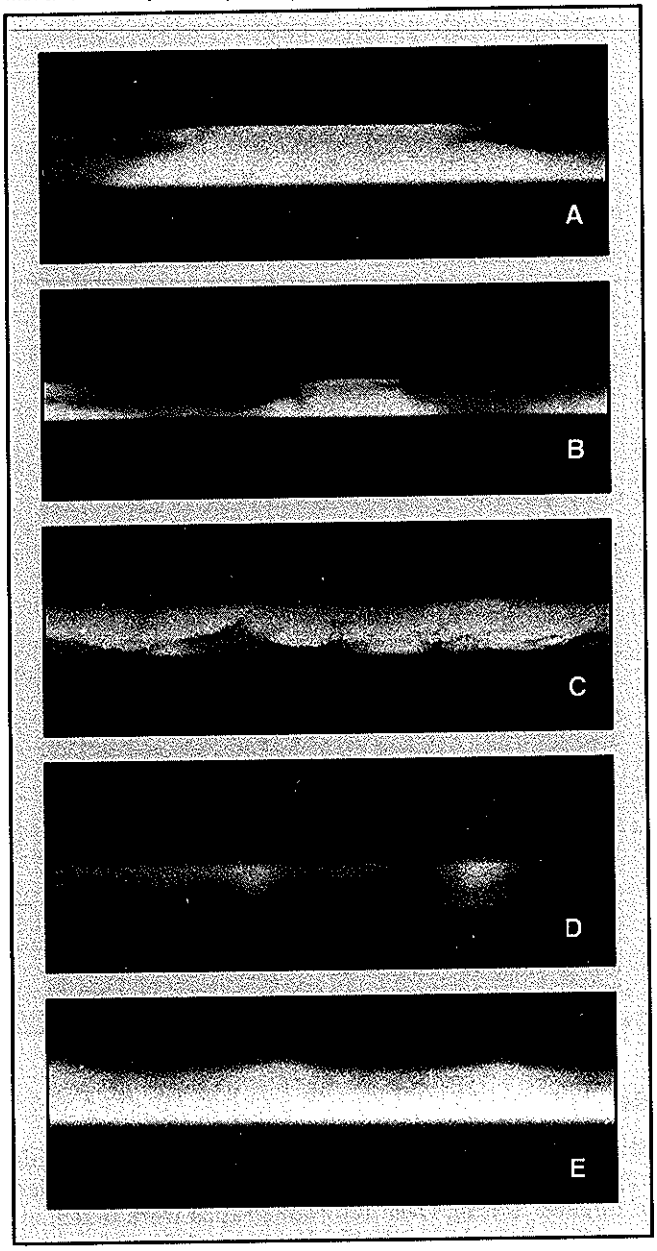
Flash X-ray radiography (FXR) uses a brief but intense flash of X radiation to produce a single stop-motion image with information about the mass density of a substance. The X rays emanate from a small area in an X-ray tube known as the "focal spot." The degree of X-ray penetration depends on the atomic composition of the material and its thickness. A void region in an object will appear as a dark spot on the film when it is developed. The film or radiograph is thus a shadow picture of an object that has been placed in the path of the X rays.

FXR's ability to penetrate fluids that are opaque to light and its ability to produce a permanent visible film record of an object without damaging it make the technique an important and versatile analytical method. This technique has been used since the 1940s. It has been applied in ballistics testing, biomedical analysis, and nuclear technology. Recent work at IPSAT has demonstrated that FXR is a useful technique for studying kraft black liquor sprays (*8*), sheet formation (*9*), and flows in a model short-dwell coater (*10*). Our study represents the first application of FXR techniques to impulse drying.

The system used in this study is a commercially available unit from Hewlett Packard, which generates a 30-ns pulse of 300-keV X rays. The device consists of a control unit and a pulse generator containing the X-ray tube. The X-ray tube has beryllium windows, which allows for low-energy, soft X rays (i.e., below 5 keV) to pass through. Soft X rays allow for higher dosage and better contrast; hence, they are useful in observing low-density objects (*11*). Hard X rays, on the other hand, have greater penetrating power but less contrast. The entire apparatus can be controlled from outside an enclosed chamber to shield the operator from radiation. A detailed description of the equipment and the principles of flash X-ray radiography are given elsewhere (*10*) and will not be covered further here. The relative locations of the FXR device, the targeted object, and the film were adjusted to obtain the best resolution and contrast. Details are given elsewhere (*12*).

X-ray-absorbent tracer solutions can be added to a fluid to help observe flow structure with FXR, just as dye can be added to a transparent liquid to observe flow. Triantafillopoulos and Farrington (*10*) examined aqueous solutions of tungsten, lead, and silver salts for use as X-ray tracers. These tracers (metal elements with high atomic number and density) provide the contrast needed to help reveal flow characteristics. Triantafillopoulos (*13*) and Spencer (*14*) compared a variety of tracer solutions for use in imaging coating flows and recommended silver nitrate for its high X-ray absorption and high solubility

4. Radiographs of impulse drying and wet pressing events in linerboard handsheets. (A) impulse drying at 225°C. (B) impulse drying at 245°C. (C) impulse drying at 315°C. (D) impulse drying at 315°C. (E) wet pressing with a room-temperature platen. (1 ms, 440-g/m² sheet, and 29% solids.)



in water. Thus, we chose silver nitrate solution as the tracer for this study.

Press simulation

A variety of wet pressing simulators have been used to obtain the typical bell-shaped pressure-time profile of a roll press. We used a device known as a Wahren-Zotterman falling-weight, press-nip simulator (*15*). (Part of the device is shown schematically in Fig. 2.) This device can accurately duplicate press nip impulse characteristics (*16*). The operation of the apparatus is simple. A platen released from a specified height impacts a wet sheet and felt, compressing the two against a stationary lower platen. After impact, the falling platen rebounds and is restrained, preventing a second impact.

While the nip residence time of the falling-weight press simulator was less than 20 ms, contact times of up to 55 ms could be achieved by adding rubber pads beneath the lower platen. The upper platen of the press simulator we used contains an electric cartridge heater that can provide platen temperatures up to 340°C (650°F).

Both platens were specially machined for this work. The top section of the lower platen is rectangular, with dimensions of 1.9 × 7.6 cm. A similar rectangular piece on the upper platen measures 1.3 × 5.2 cm. The bottom section of the lower platen was cut out to fit over a load cell. The load cell was used with an oscilloscope to obtain the pressure-time profiles of the pressing event. An adjustable film holder was added to the lower platen to hold the film cassette in place.

The falling upper platen acted to trigger the FXR system. A triggering device using a photoelectric sensor was connected to a digital delay generator on the FXR system console; delay times could be set manually. The photo sensor was triggered by a strip of metallic tape attached to the upper carriage as it fell toward the bottom platen.

Experimental procedure

Strips from thick linerboard handsheets (440–490 g/m², unbleached kraft, 650 mL CSF) were cut to the dimensions of the upper platen and were placed on felt strips of the same size. Thick sheets were needed to obtain the desired resolution. The handsheets had been couched and pressed lightly to obtain 25–29% solids. In addition to unbleached kraft, fluff pulp and blotter paper (similar basis weights, 35–40% solids) were used in some tests.

To improve the visualization of liquid motion in paper, drops of silver nitrate tracer solution were added to the top surface of the sheet prior to pressing. The drops were added with a micropipette to the center of the sheet to reduce possible edge effects.

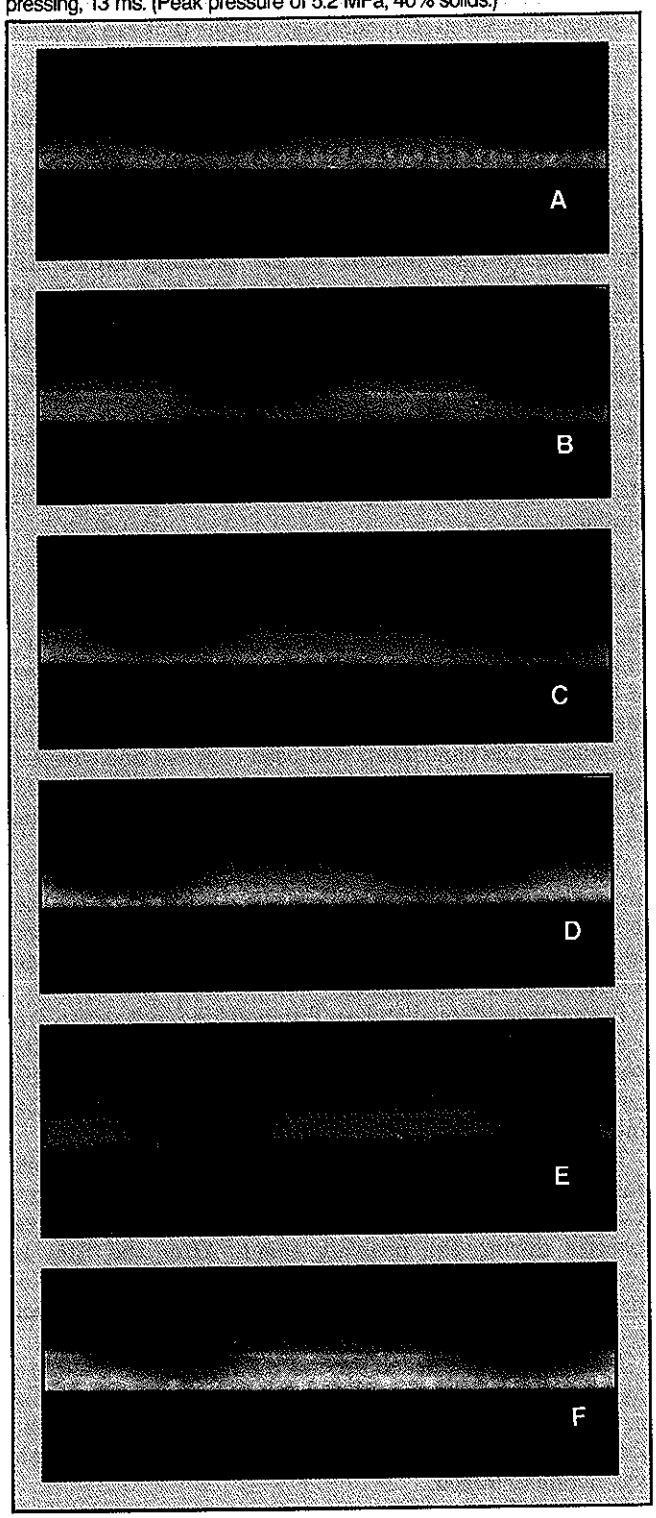
Both unconditioned and conditioned Nomex® felts were used in the experimental runs. The unconditioned felts were at room temperature and low (air-dry) moisture content. The conditioned felts were at room temperature and 30% moisture.

During the pressing event, X rays are sent in a short burst through the sheet and felt and are captured on an X-ray-sensitive film. The film is kept in a protective cassette during the pressing event. After the film is developed (*17*), the location of the tracer fluid in the *z*-direction can be observed. Various delay times can be set to observe the fluid motion at different times in the nip.

All pressures recorded during the pressing event were peak pressures obtained from the pressure-time profile on the oscilloscope. Unfortunately, the actual pressure that occurred at the particular event time of the radiograph was not determined.

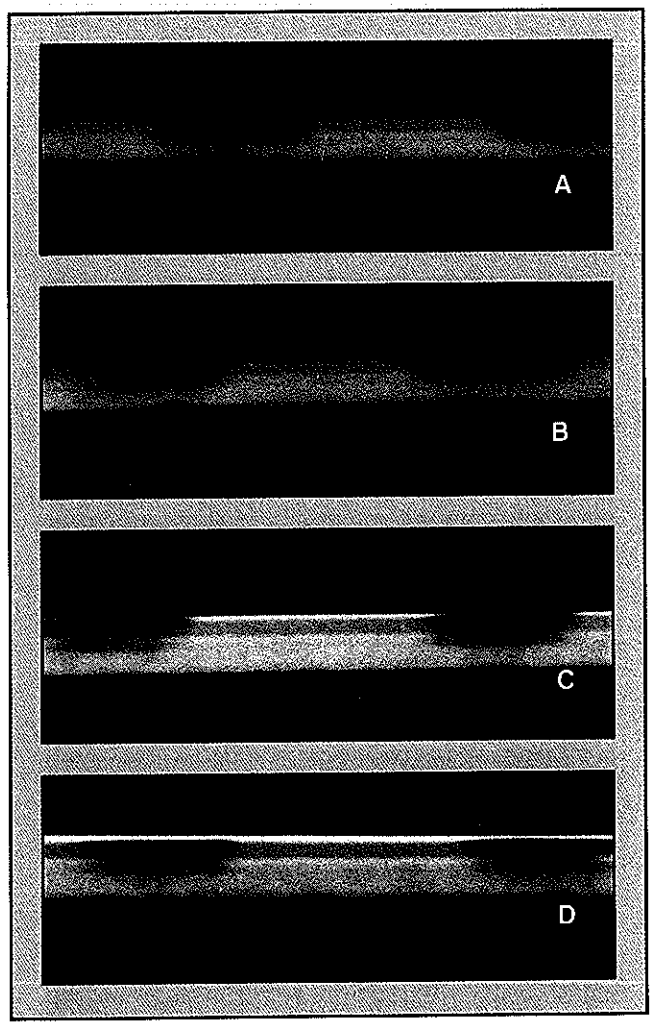
Many different temperatures, pressures, and event times were examined. In addition, different volumes and concentrations of silver nitrate solution were studied. Volumes added ranged from 5 to 50 μL per drop. Concentrations ranged from 25% by weight to a saturated solution. As mentioned, the tracer solution was added to the center of the sheets. The idea was to keep the fluid inside the sheet and prevent it from being ejected out the

5. Radiographs of impulse drying and wet pressing events in fluff pulp sheets. Event times progress from 11 ms to 13 ms. (A) impulse drying, 295°C, 11 ms. (B) wet pressing, 11 ms. (C) impulse drying, 300°C, 12 ms. (D) wet pressing, 12 ms. (E) impulse drying, 305°C, 13 ms. (F) wet pressing, 13 ms. (Peak pressure of 5.2 MPa, 40% solids.)



edges. Volumes between 20–25 μL per drop worked well with the types of handsheets used in this study. Concentration was not as critical; however, below 40% of silver nitrate by weight the desired contrast for flow visualization could not be achieved.

6. Radiographs of impulse drying in fluff pulp sheets on conditioned Nomex felts. Event times progress from 10 ms to 14 ms. (A) 300°C, 10 ms. (B) 290°C, 11 ms. (C) 290°C, 13 ms. (D) 290°C, 14 ms. (Peak pressure of 5.2 MPa, 35% solids.)



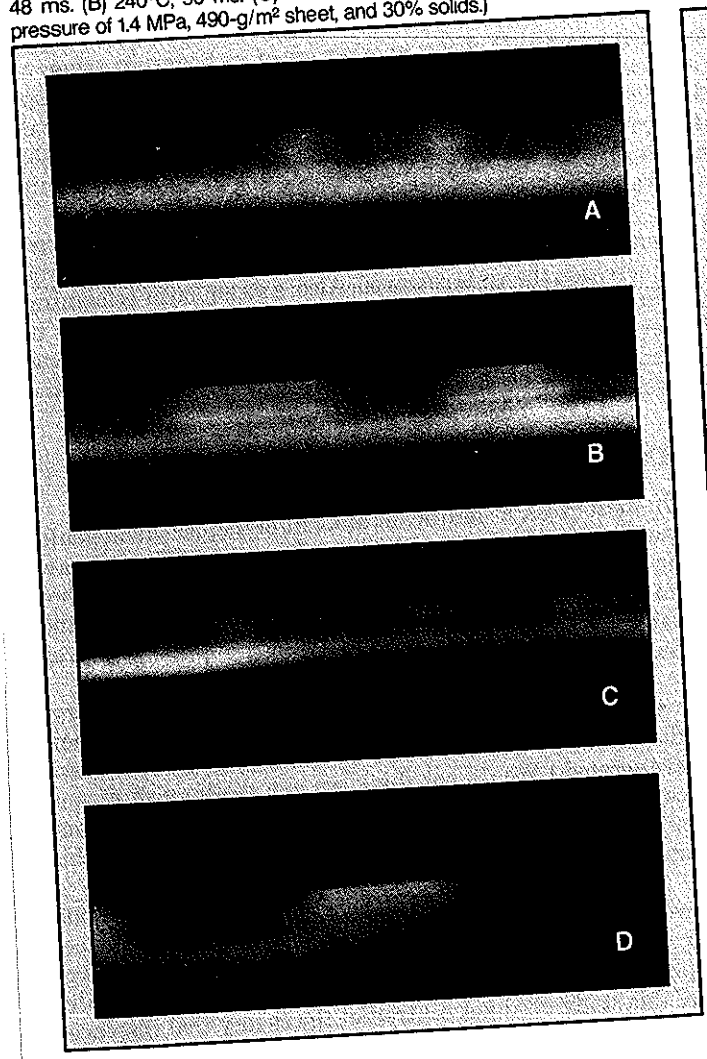
Results

Many experimental runs were completed using this approach to develop the FXR technique for visualization of impulse drying. Over 100 radiographs were taken, all of which show the thickness direction of the paper web and felt during the pressing event. The addition of silver nitrate solution to the upper layers of the sheet allowed us to track the fluid motion in the z-direction.

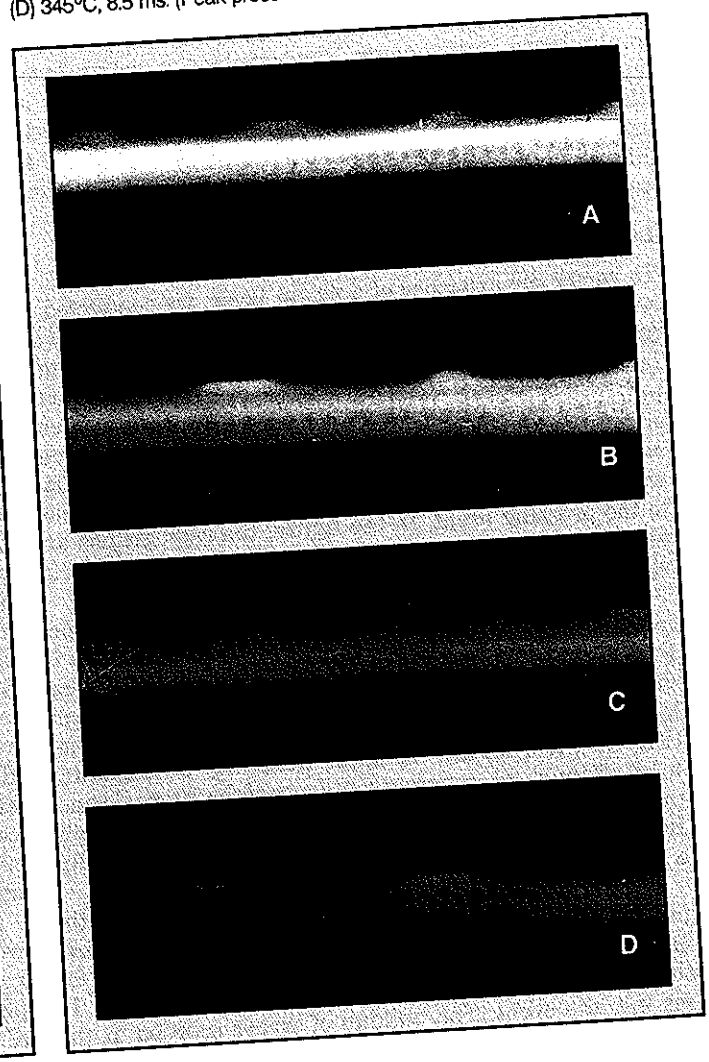
Interpretation of radiographs

Figure 3A is a radiograph of a linerboard sheet on top of a Nomex felt taken 7.5 ms into an impulse drying event. The contrast between the sheet and the felt is clearly seen. The denser paper web absorbs more X rays and appears darker than the press felt. The black regions above and below the sheet-felt combination are the two pressing heads. No silver nitrate solution was added to the sheet. The figure shows that without the use of opaque fluid tracers, little information can be obtained regarding fluid motion in the web.

7. Radiographs of impulse drying with extended nip residence times. Linerboard sheets are used with unconditioned Nomex felts. (A) 195°C, 48 ms. (B) 240°C, 50 ms. (C) 270°C, 46 ms. (D) 295°C, 45 ms. (Peak pressure of 1.4 MPa, 490-g/m² sheet, and 30% solids.)



8. Radiographs of impulse drying in blotter paper with unconditioned Nomex felts. (A) 340°C, 4.5 ms. (B) 320°C, 6.5 ms. (C) 330°C, 7.5 ms. (D) 345°C, 8.5 ms. (Peak pressure of about 4.8 MPa, 37% solids.)



A linerboard sheet and felt combination resting on the lower platen can be seen in Fig. 3B. This radiograph was taken before the impact of the upper platen. The dark spots are silver nitrate drops that were added to the sheet. Excellent contrast can be seen between the X-ray-absorbing silver nitrate solution and the paper web. Further details of the press felt can also be seen.

Early results

The first set of radiographs taken was encouraging. **Figure 4A–D** are radiographs of four different linerboard sheets during impulse drying, all at an event time of 1 ms. Figure 4E is a radiograph of pressing under similar conditions with an unheated platen. An oscilloscope had not been connected to the load cell for this set of experiments. Thus, the total nip residence time and the peak pressure applied were not recorded at the time of the event. We later determined that the total nip residence time was 2 ms and the applied peak pressure was approximately 30 MPa (4500 psi).

Even though the pressure applied is much greater and the nip residence time is much less than is typical for commercial pressing, some interesting results are evident. The events in Fig. 4A and 4B show the movement of silver nitrate solution in the web and felt. The temperature of the upper platen was similar in both cases (225°C and 245°C). The solution of silver nitrate has advanced through the web, and a lighter region appears in the upper layers of the sheet above the solution. This region indicates a low-density region now devoid of silver nitrate.

We think that what we are seeing here is the dry, vapor-filled zone in the upper layers of the web, because a two-phase zone would still contain substantial amounts of tracer. The absence of silver nitrate solution in the upper region of the sheet suggests that vapor has displaced the liquid. Figure 4E indicates that tracer solution in the upper regions of a sheet can be smeared or spread out through a sheet but cannot be removed from the top of the sheet through pressing alone.

The two events in Figs. 4C and 4D were carried out at a higher temperature (315°C). The movement of silver nitrate solution is again evident; however, this time it appears much less uniform. Displacement seems to be further into the sheet and felt. This gain in displacement

may be caused by the increase in temperature. The temperature increase would improve heat transfer and thus the displacement of the liquid water.

The applied pressure was extremely high in this set of preliminary experiments. Nevertheless, a vapor layer appears to exist in the upper layers of the sheet early in the event. In fact, recent work by Lindsay (*17*) suggests that the displacement mechanism might be enhanced at higher pressures because of improved heat transfer compensating for the decrease in sheet permeability.

Impulse drying vs. wet pressing

To verify the existence of a steam layer, we conducted a set of experiments comparing impulse drying to wet pressing. **Figure 5A-F** shows sets of radiographs taken in sheets of fluff pulp for both types of drying. The peak pressure of 5.2 MPa (750 psi) and the initial solids content of 40% were held constant in each event. The event times were varied. A drop of 20 μL of 50% silver nitrate solution was added to most sheets in three different locations prior to the pressing event. In the figure, the radiographs are arranged in increasing order of event time and should be viewed in pairs (i.e., A and B, C and D, E and F).

An accumulation of tracer solution at the felt-paper interface can be observed in these events, most clearly in Figs. 5A and 5B. A steam layer is evident in the impulse-dried sample at an event time of 13 ms (Fig. 5E). No steam layer is present in the corresponding wet-pressed condition (Fig. 5F). In Fig. 5E, the upper head may be beginning to lift off the sheet, apparently because of the internal vapor pressure in the sheet. What is not seen in these photographs is the penetration of low-density steam regions through a substantial portion of the paper.

An additional set of radiographs taken during the impulse drying of fluff pulp sheets is shown in **Fig. 6A-D**. (There were no corresponding wet pressing events for these runs.) A steam layer is again evident at 13 and 14 ms into the event. The buildup of tracer solution at the sheet-felt interface is also evident.

Linerboard sheets

Figure 7A-D shows various radiographs of impulse-dried linerboard sheets on top of unconditioned Nomex felts. The experimental apparatus was changed so that a longer nip residence time could be achieved (approximately 55 ms). The lower platen rested on top of a large stack of rubber pads.

In using this setup, it was not possible to get the film directly against the platen, so more scattering occurred between the object and the film, which was manifested as a decrease in clarity. Nevertheless, silver nitrate movement can be seen. The silver nitrate solution in Figs. 7A and 7B seems to be moving in the transverse direction directly below where the drops were placed. Drops of 20 μL were added in Fig. 7B and 10-μL drops were added in Fig. 7A.

Figure 7C shows a similar impulse-drying event in which silver nitrate was added to the sheet to a total of 40 μL. A buildup of silver nitrate is again evident at the sheet-felt interface. In Fig. 7D, a light zone at the top of the paper can be seen in the region between the silver nitrate drops. This observation may indicate a two-phase zone with low saturation; silver nitrate solution appears to still be present in the regions where tracer drops were added.

Blotter paper

Figure 8A-D shows another set of radiographs taken of two wet blotter paper samples on an unconditioned press felt and rubber pads during impulse drying. The peak pressure was held at 4.5 MPa (650 psi) while the temperatures ranged from 320°C to 345°C. The total nip residence time was 18 ms.

The figure shows that at 4.5 ms into the event, a large amount of air remains in the felt. As the event time increases, the air is removed. Also, a steam layer is forming in the upper layer of the sheet next to the hot surface in every event. Only a small amount of tracer solution was added to the sheets (5 μL/drop). Thus, no movement of the solution can be seen.

Discussion

In most cases, a significant amount of displacement could not be directly observed in the radiographs. What we saw in some cases was a thin, low-density zone near the hot metal platen, which often was not observable until the latter portion of the impulse drying event. In no case was such a layer seen in the wet pressing cases.

We believe that the low-density zone represents a dry, vapor-filled layer from which the liquid has been displaced. (A small amount of the liquid will also have evaporated.) We do not think we can distinguish a zone containing both vapor and fluid phases (and hence silver nitrate) from a saturated zone in the radiographs of this study.

Numerical modeling work has indicated that a dry zone would grow slowly in impulse drying and that displacement of liquid would occur as a partially saturated two-phase zone grows into the sheet (*5, 17*). Thus, the results of this study need not contradict the theory that displacement occurs in impulse drying; instead, our results may correlate with the predicted slow growth of a dry zone. Had the sheets been thinner, a decrease in resistance to flow would probably have allowed the vapor zone to grow more.

In any case, our results do suggest that vapor can form in the nip during impulse drying. If vapor is present, then the dewatering mechanisms of both displacement and rewet reduction can occur, as previously hypothesized.

The observed buildup of silver nitrate solution at the felt-paper interface confirms new findings recently published by Catton and Lee (*18*), who investigated two-phase flow in layered porous media. Catton and Lee derived equations for the change in saturation at an interface between dissimilar porous media with two-phase (gas-liquid) flow occurring across the interface. Their results compared well with experimental data. The liquid saturation was found to be fairly uniform in each of the layers except near the interface. When flow was from high to low permeability, a buildup of gas occurred at the interface. When flow was from low to high permeability, as is the case when water flows from paper to a felt, the gas phase was depleted at the interface, and there was an accumulation of liquid. These results contradict predictions made by Bear (*19*) using older theory.

A buildup of liquid at the paper-felt interface also has important implications for rewet which may occur in pressing events. A recent thesis (*20*) explores three possible mechanisms of rewetting: suction forces, capillary forces, and film splitting. An increase in saturation at the interface may give increased credence to the film splitting theory. Furthermore, if the interface is saturated, there is an abundance of fluid available for both capillary and suction-driven uptake into the paper. On the other hand, if vapor pressure is sustained during impulse drying, all mechanisms of rewet will be opposed as the sheet leaves the nip. The role of rewetting in impulse drying is currently being explored in a separate study (*21*).

Summary and conclusions

Applying FXR techniques to impulse drying proved to be beneficial. The use of silver nitrate as an X-ray absorbing tracing fluid provided a means for tracking fluid motion during the pressing event. In some cases, however, the vapor zone was best seen in regions where no silver nitrate was initially present.

A steam layer or dry zone can form in the upper layers of the paper web during impulse drying. However, more research is needed to understand the significance of the vapor zone and to explore the two-phase zone which may exist. If no two-phase zone can be found, for instance, then proposed mechanisms of impulse drying would need to be altered significantly. Improved FXR techniques and equipment may be needed to resolve saturation gradients that occur in the sheet.

Our work also indicates that a buildup of liquid is occurring at the sheet-felt interface during impulse drying and wet pressing events. This phenomenon supports the idea that film splitting can contribute to rewetting.□

Literature cited

1. Devlin, C., Ph.D. thesis, The Institute of Paper Chemistry, Appleton, June 1986.
2. Burton, S. W., Ph.D. thesis, The Institute of Paper Chemistry, June 1986.
3. Sprague, C. H. and Burton, S. W., Proceedings of the PIRA International Conference on New Technologies in Web Consolidation and Drying, Vol. II, PIRA, Surrey, England, 1986, Session 4, Paper No. 15.
4. Lavery, H. P. High Intensity Drying Processes—Impulse Drying, Second Annual Report for U.S. Dept. of Energy under Contract No. DE-FG01-85CE40738, The Institute of Paper Chemistry, Appleton, Feb. 1988.
5. Lindsay, J. D., Advances in the modeling of impulse drying, 1989 Engineering Conference Proceedings, TAPPI PRESS, Atlanta, to be presented.
6. Dreshfield, A. C. and Han, S. T., Tappi 39(7): 449(1956).
7. Macklem, E. A. and Pulkowski, J. H., 1988 Engineering Conference Proceedings, TAPPI PRESS, Atlanta, p. 447.
8. Farrington, T. E., Tappi J. 71(2): 89(1988).
9. Farrington, T. E., Soft X-ray Imaging Can Be Used to Assess Sheet Formation and Quality, IPC Paper Tech. Series No. 240, June 1987.
10. Triantafillopoulos, N. G. and Farrington, T. E. Flash X-ray Radiography Techniques for Visualizing Coating Flows, IPC Paper Tech. Series No. 274, Jan. 1988.
11. Carbonnier, F., Nondestructive Testing Handbook, Flash Radiography, ANST, Columbus, Ohio, 1983.
12. Zavaglia, J. C., M.S. thesis, The Institute of Paper Chemistry, Appleton, March 1989.
13. Triantafillopoulos, N. G., A study of coating flows with flash X-ray radiography: A-490, Progress Report Four, The Institute of Paper Chemistry, Appleton, Oct. 1987.
14. Spencer, Dennis, James River Corp., Neenah, Wis., personal communication, 1988.
15. Zotterman, C. and Wahren, D., Paper Trade J. 162(16): 37(1978).
16. Chang, N. L., Nett, M. R., and Beck, D. A. J., Pulp Paper Sci. 12(2): J39(1986).
17. Lindsay, J. D., The physics of impulse drying: new insights from numerical modeling, to be presented at the Ninth Fundamental Research Symposium, Cambridge, England, Sept. 16-22, 1989, PIRA, Surrey, England.
18. Catton, I. and Lee, H. S., Two-phase flow in porous media, Proceedings of the 1987 ASME-JSME Engineering Joint Conference, ASME.
19. Bear, J., Dynamics of Fluids in Porous Media, American Elsevier Pub. Co., New York, 1972.
20. Jaavidaan, Y. Ph.D. thesis, Chemical Engineering Dept., University of Maine, May 1987.
21. Rogers, J., A study of rewetting in impulse drying using flash X-ray radiography, M.S. thesis, The Institute of Paper Chemistry, Appleton, in progress, 1989.

Thanks to Dennis Spencer and Nick Triantafillopoulos for help with the flash X-ray equipment and procedures. Gerry Kloth was also instrumental in troubleshooting the many problems encountered along the way.

Received for review June 1, 1989.

Accepted June 19, 1989.

Presented at the 1989 Engineering Conference.