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ABSTRACT

A new dewatering process based on gas-liquid displacement has been experimentally evaluated. The process, displacement dewatering, uses a pressurized air or steam phase to expel free liquid water from paper while the paper is simultaneously under mechanical pressure. The objective is to efficiently dewater paper while maintaining bulk, in contrast to conventional pressing operations which remove water solely through volume reduction of the web. Displacement dewatering also differs from through drying, in which a gas phase blows through the paper to evaporate water. In displacement dewatering, a true displacement process is desired in which a gas-liquid interface is maintained.

Recent experimental results with bench-scale equipment are reported, and tentative implications for commercial technology are discussed. While the data do suggest that displacement dewatering can be an efficient dewatering process for some grades of paper, the objective of maintaining high bulk has not yet been demonstrated. Subjecting paper to low mechanical pressure for the relatively long nip residence times required in displacement dewatering may induce creep effects which can lead to higher than expected densification. Densification can be especially severe when superheated steam is used due to thermal softening of the fibers. Improved strategies are required to tap the potential of a displacement dewatering process.

INTRODUCTION

The capabilities of the press section have progressed significantly in the last several decades, allowing ever higher dryness levels to be achieved. However, higher dryness typically means higher sheet density. For those grades of paper where high density is not desirable, the trade-off between bulk and dryness poses unwanted constraints on the papermaker. Energy-efficient dewatering techniques which decouple density and dryness could be of significant benefit to the industry. One proposed means of achieving this objective is through displacement dewatering, in which a pressurized gas phase is used to drive liquid water out of a mechanically compressed sheet. The externally imposed gas pressure could supplement the normal hydraulic pressure gradient in a sheet that forms as the sheet is compressed. Because gas pressure would increase and extend the usual hydraulic pressure, driving more water out of the sheet, higher dryness levels could be achieved without further mechanical compression of the sheet. Dryness and density could thus be decoupled to a degree, potentially giving the papermaker added control over sheet properties and possibly a lower energy demand in the dryer section.

In most pressing operations, increasing the press impulse is not effective in raising the outgoing dryness beyond about 45-50%. The details vary widely from press to press, but once a compression-controlled regime is reached, higher impulse brings only marginal dryness gains. Displacement dewatering, however, has the potential of increasing the dryness to even higher levels, for the free water in a sheet can still be removed by the gas in a compression-controlled regime. If displacement dewatering could be commercially implemented, it may give the papermaker a new choice between higher dryness at the usual density or lower density at the former dryness level, or something in between.

In this paper, displacement dewatering refers to a process in which a gas phase is used to drive out a liquid layer in a compressed sheet. If true displacement dewatering is achieved, relatively little vapor would be required to pass through the sheet - ideally only enough to uniformly displace the free water in the interconnected pores of a compressed sheet. This concept, at least in its idealized form, differs from through drying or impingement drying, in which large volumes of heated air are used primarily to evaporate water in the sheet, although the process of through drying also removes some water by entrainment. While the objective is to decouple density and dryness, displacement dewatering still requires substantial applied pressures to saturate the sheet and create an interconnected liquid layer which can be displaced by gas. In practice, the gas is likely to break through some pores in the sheet and remove water by entrainment and evaporative drying, but the objective is uniform displacement.

Such a displacement process would be of interest in grades such as linerboard, boxboard, and some printing papers and specialty products where the sheet is too heavy for through drying or other techniques suitable for lightweight, highly porous paper, but where bulk is still desired. In the displacement process under consideration, such a sheet would be subjected to moderate mechanical pressures to increase sheet saturation, probably in the range of 100-300 psi, while simultaneously being exposed to compressed gas. One possible implementation is shown in Figure 1. The apparatus envisioned here is like a suction roll operating in reverse, with multiple low-pressure long nip shoes to maintain the displacement process for a sufficient time.

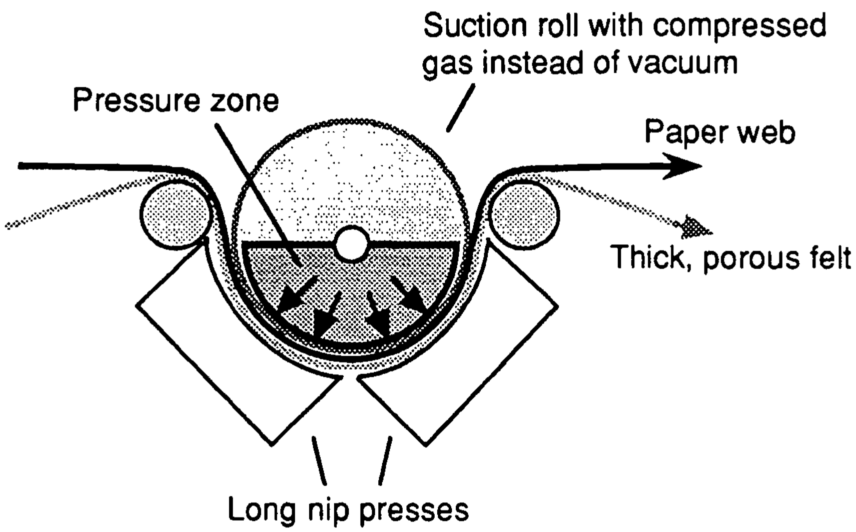

Figure 1. Possible implementation of the displacement dewatering concept.

This paper describes the recent results of an on-going study on the potential of displacement dewatering, and attempts to evaluate the possible commercial importance of this technology.

PREVIOUS WORK

The use of gas to assist dewatering is hardly new. Indeed, a number of the concepts explored in this study were found to have been proposed, if only in passing, in a variety of prior patents and articles. A careful discussion of what has been done in the past is thus needed to clarify the contributions of the present study.

Through Drying Concepts

Entrainment and Displacement

In a patent granted in 1966, Holden (1) proposed several devices which would blow air through a wet web to remove water. Holden's concept was to dislodge and entrain water in a porous sheet by blowing air through the z-direction over a sufficiently long time (>50 msec). While he proposed several devices, the one most relevant to the present study is shown in Figure 2. In this apparatus, light mechanical pressure was to be applied to the sheet by felt tension as the sheet received air flow from a perforated roll.

Holden's concept was extended by Kawka and co-workers (2-9) over a number of years. Kawka used some of the devices as proposed by Holden, such as that in Figure 2, and invented others which also passed gas through a sheet under low mechanical pressures applied by porous belts, wires, or felts (2-4). Kawka's work focuses on blowing air through paper, especially absorbent papers and boards. In one study, for example, unheated air pressures from 0.01-0.08 MPa were used with exposure times of 0.1-1.0 s to dry absorbent papers (5). Solids content was raised from 10% to 30-40%, although a 28 gsm napkin tissue was dried from 18% to 87% solids in 0.5 seconds using air heated to 130°C.

In general, the blow-through process, with light mechanical compression, is severely limited in the dryness that can be achieved in short times. For example, with bag paper of 70 gsm, Kawka reports solids out of up to 43% obtainable with an 0.6 second exposure time of room-temperature air passing through the sheet (6). Initial solids content was 31%. In a thorough, recent study of through-drying with room-temperature air, Kawka reports that the time required to remove the free water in paper is about 5 seconds with air pressures on the order of 0.1 MPa (7). (As will be seen below, any blow-through or displacement process will not be able to remove much water on the short time scales characteristic of conventional wet pressing.)

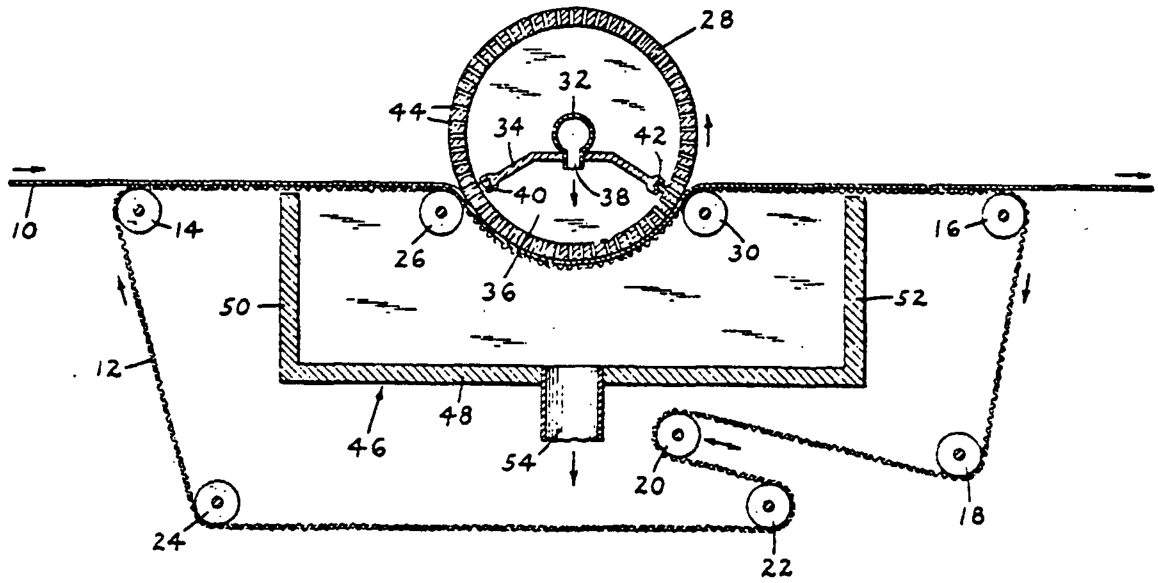

Figure 2. A blow-through dryer proposed by Holden (1).

The theory of through drying is treated in (8). While Kawka claims that displacement of water from pores takes place in wet sheets with initial solids below 25%, more important seems to be the entrainment of water particles which occurs as air passes through the sheet with velocities on the order of 100 m/s (9). He states that the entrainment process works best at solids contents around 35%.

All devices used by Kawka and Holden have the following characterisics:

- low mechanical compression (several psi) on the sheet
- long exposure times (0.05 - several seconds)
- modest applied gas pressures (typically 1-30 psig)
- air as the displacing medium, typically unheated
- low operating speeds (< 300 m/min).

The blow-through concept has been aimed primarily at lightweight grades such as towel and tissue as well as bag papers. One article mentions application to heavyweight board, but no data are given (9).

Thermal Processes (Evaporation)

Through drying is a well developed technology in which heated air is passed through a highly porous sheet under minimal compression (10-13). Because the hot air contacts water across a large surface area inside the sheet, evaporative heat transfer is very efficient. Displacement is not likely to occur, but some liquid may be removed by entrainment. Tissue and toweling are prime grades for through drying, although various filter grades, roofing felts, wiper grades, and many wet-laid nonwovens can be used (12).

Both cylindrical and flat bed through dryers are used. One example of a cylindrical though dryer is shown in Figure 3. A porous roll can be sufficiently strong to withstand high pressure differentials. Using a roll with a highly open honeycomb structure, Randall (14) reports pressures up to about 0.03 MPa or 5 psi, while a drilled suction role could support still higher pressures at the cost of less open area. With high differential pressures, sheet transfer may be impaired. Flat bed through dryers, as shown in Figure 4, pass the sheet between high and low gas pressure zones on a conveyor device. Sheet transfer is easy, but the process is limited to lower pressures.

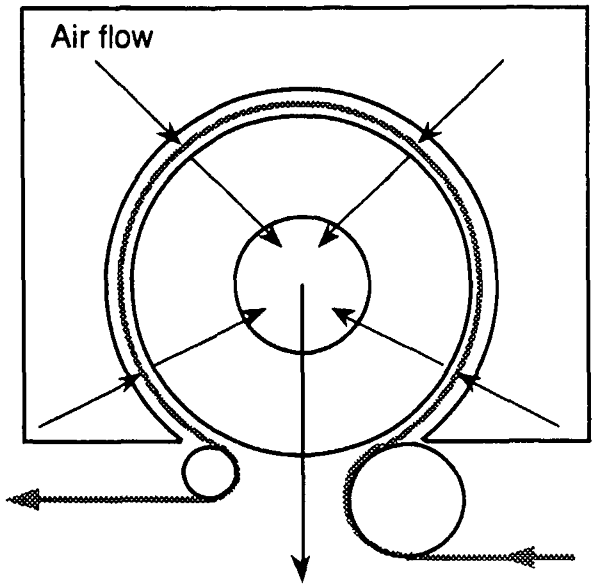

Figure 3. A cylindrical through dryer.

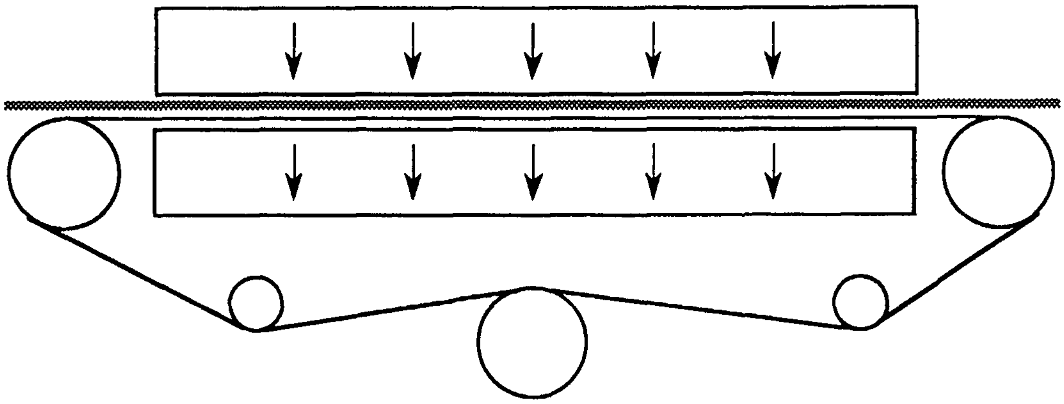

Figure 4. A flat bed through dryer.

High velocity gas impingement in tandem with through drying has been investigated and patented by Burgess et al. at the Pulp and Paper Research Institute of Canada (15,16). In this "Papridryer" system, vacuum pressure inside a drilled suction roll pulls hot air through the sheet, decreasing boundary layer heat transfer resistance in impingement and causing internal heat transfer in the sheet.

Other Dewatering Processes

Impulse drying, a novel thermal dewatering process under development at The Institute of Paper Science and Technology, may induce a displacement process which enhances liquid water removal from a sheet. In this process, a web and a felt pass through a nip in which one roll is heated to around 250°C (17,18). During the period of brief but intense heat transfer, with peak heat fluxes on the order of 4 MW/m^2, a high-pressure steam zone may form in the nip which can displace some liquid water or at least resist rewetting (19,20).

A related concept of gas-liquid displacement in dewatering was addressed in a patent awarded to Gottwald, et al., in 1967 (21). Their proposed device was a heated drum at 120-250°C, wrapped with a wet web held in place by a porous belt under enough tension to cause at least 5 psi of pressure on the web. They claim that vapor generated at the drum-web interface would drive liquid water into the porous belt, reducing the evaporative load on subsequent dryers. The proposed physics seem questionable, as a saturated liquid layer is not likely to exist under these conditions, but the possibility of *in-situ* steam-liquid displacement clearly was envisioned.

A novel concept using a high velocity gas nozzle to remove water by atomization was patented by Clemens and Morton in 1977 (22). This method is related to some versions of through drying in that entrainment of liquid water takes place, but Clemens and Morton use a small, high-pressure, high-velocity jet from a nozzle which is claimed to remove water from low-density webs at web speeds as great as 6,000 feet/min (30 m/s). Their objective was to remove water without decreasing bulk. The process is intended for very light grades such as tissue.

The IPST Displacement Concept

The displacement dewatering concept discussed here employs conditions well outside the realm of the through drying processes discussed above. Specifically, the dewatering process under consideration:

- employs mechanical pressures great enough to liberate a substantial amount of water in the sheet, with conventional pressing pressures being possible;
- is intended to use brief intervals of time, less than 0.3 seconds and preferably under 100 msec to permit operation at practical speeds;
- seeks to raise solids levels of incoming sheets at 20-30% solids to beyond 40-50% to save drying energy as well as offer better control over bulk.

The current study actually began in 1985 with exploratory work done by Wahren, Ahrens, and Sprague at the Institute of Paper Chemistry in Appleton, Wisconsin (now the IPST in Atlanta, Georgia). The work reported here is a continuation of the same project, resumed in 1987, which has suffered a number of major delays and interruptions over the past several years. Early results of this study were reported by Sprague (23). Room temperature air only was used in a series of brief experiments using lightweight sheets with several displacement devices. The equipment used posed a number of problems. In particular, drying was nonuniform due to improper air flow distribution. Large drilled holes in the platens led to nonuniform mechanical pressures. Air leakage around the edge of the sheet during displacement also appears to have been a problem. The new equipment for this phase of the study was designed to overcome these problems, as described below.

Sample results from the early portion of this project (23) are shown in Figure 5. Here a sheet was subjected to mechanical compression between plates with a number of holes. After 60 ms of compression, a valve released a burst of compressed air which continued for another 60 ms, with gas pressure maintained past the end of the pressing event. The low gain in solids when no air was used must reflect the inefficiency of wet pressing between two drilled platens; conventional wet pressing under similar press conditions would have undoubtedly given much better dryness levels.

In examining trends in density and dryness, Sprague found evidence that gas displacement can allow significant water removal to be achieved without the normal degree of densification. This possibility will be examined in more detail in this paper.

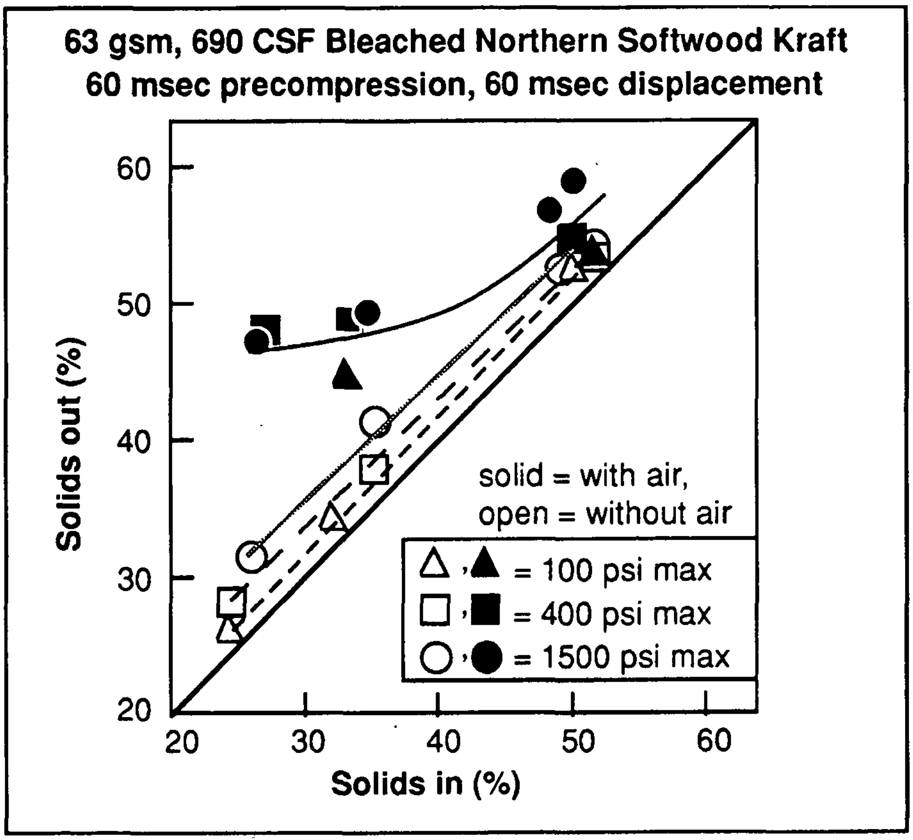

Figure 5. Dewatering results obtained with early displacement dewatering equipment at the IPST (23).

THEORY OF DISPLACEMENT DEWATERING

Speed of Displacement

One simple but key issue in displacement dewatering is the length of time the gas pressure must be applied. Consider the one-dimensional motion of a stable gas-liquid interface driven by constant gas pressure through a uniform porous medium of thickness L and permeability K. The gas liquid interface is at position x, with $x = 0$ at the flow exiting side of the sheet. The pressure drop across the sheet is ΔP. Neglecting inertial effects and neglecting the viscosity of the gas phase, we can apply Darcy's law to determine the interface velocity:

$$V = \frac{-dx}{dt} = \frac{K}{\varepsilon\mu}\frac{\Delta P}{x} \tag{1}$$

where V is the interface velocity, ε is the sheet porosity, and μ is the liquid viscosity. The time required for the interface to move across the entire porous medium beginning at the upper surface ($x=L$) is given by integration:

$$\int_L^0 -x\,dx = \int_0^t \frac{K\Delta P}{\varepsilon\mu}\,dt' \tag{2}$$

resulting in

$$t = \frac{\varepsilon\,\mu\,L^2}{2K\,\Delta P} \tag{3}$$

where t is the required time. Let us apply typical conditions for a linerboard sheet. The viscosity of the warm water could be 0.0007 Pa-s (0.7 cp), the compressed sheet might be 0.2 mm (8 mils) thick with a permeability of 4.0×10^{-16} m^2 and a porosity of 0.6. If gas is applied at a pressure of 0.5 MPa (72.5 psi), Equation (3) predicts that the gas-liquid interface will move across the sheet in 42 ms. A thicker or less permeable sheet will require more time. In reality, the displacement process will not be so efficient. The gas-liquid interface will not move smoothly but will break up because of inherent instabilities, which are discussed next.

Interface Stability

When a liquid is displaced in a porous medium by another immiscible fluid of lower viscosity, the interface between the phases is frequently unstable. Any small perturbation on the initially smooth interface will accelerate because of the lower pressure drop in the more mobile fluid, creating "fingers" that penetrate into the phase being displaced (see Figure 6). This phenomenon is called "viscous fingering" (24). For secondary oil recovery, it means that displacement of oil bywater or gas will be inherently inefficient, since large portions of the oil may be bypassed by viscous fingers that break through to the production well. In the paper industry, it means that a gas phase will tend to simply blow through certain paths in the paper, leaving much of the water behind.

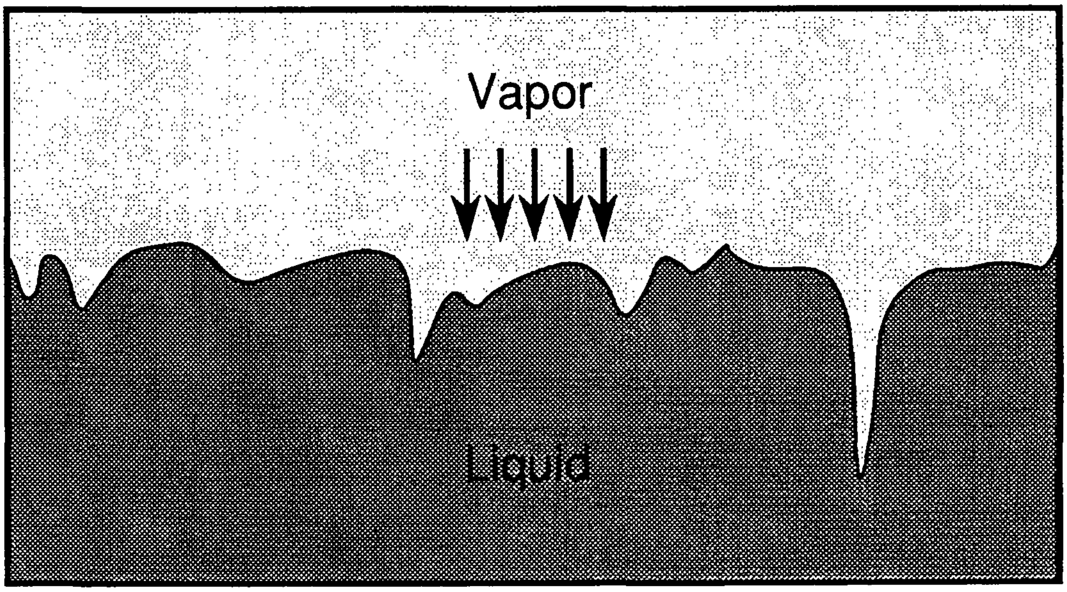

Figure 6. Viscous fingering in a porous medium as a gas displaces a liquid.

However, a number of factors have been shown to enhance stability. For example, if the viscosity of the displacing phase can be “artificially” increased, interface stability can be achieved. This artificial increase in viscosity can be achieved by using foams, which are mostly low-viscosity air but behave like a fluid with a very high viscosity due to the structure of the foam. In secondary or tertiary oil recovery, for example, foams have been used to increase the stability of displacement (25). In the paper industry, Skelton (26) has reported that application of foam to paper increases water removal by suction. Skelton writes that the reasons for this effect are unknown. The analogy to oil recovery, however, would appear to provide at least part of the explanation. The stability of the displacement process in suction is increased, and water removal becomes more efficient. Experimental work with stabilizing foams is planned for the current study, but has not yet been conducted.

Anisotropic permeability in paper can also enhance displacement stability. If the lateral permeability is greater than the normal permeability, a viscous finger could tend to spread out in the plane of the paper, thus creating a more uniform surface. Measurements of the full permeability tensor have been conducted in conjunction with the present study (27,28). The results to date indicate that the ratio of in-plane to transverse permeability is greater than unity, with an observed become "self-sealing" to some extent, making the interface more stable. The combined effects of heat transfer and condensation are believed to make superheated steam a good candidate for displacement dewatering.

EXPERIMENTAL APPROACH

Equipment

An experimental displacement device (Figure 7) was constructed for this study. The displacement device consists of two heads installed in an MTS hydraulic press (Figure 8). The hydraulic ram drives the upper head, and can control the motion and applied mechanical pressure to simulate pressing conditions. The upper head consists of a hollow chamber above a drilled bronze plate. The plate can apply mechanical pressure to paper, and at the same time allow gas pressure to be applied. High-pressure gas is released from a pressure vessel into the upper chamber by a rapid solenoid valve. The extended, tapered sides of the upper head fit over the lower head and form a seal with an O-ring that encircles the lower head. The lower head is also a hollow chamber with a drilled bronze plate on top to allow gas to pass from the upper into the lower head, and from thence into the atmosphere through a hole in the lower frame of the MTS system. If desired, the volume of gas passing through the sheet can be measured with a collection bag at the end of the exhaust line from the lower head. The gas pressure in the upper head can be released by gas passing through the sheet and into the lower head, by escaping at the end of a press event when the O-ring seal is broken, or by passing through an opening in the side of the upper head.

The bronze plates are drilled with 0.09-in (0.0023 m) holes, with a center-to-center distance of 0.125 in (0.0032 m). The open surface area is 47%. The plates are sufficiently thick (1 in or 0.0254 m) to prevent significant bowing during compres-

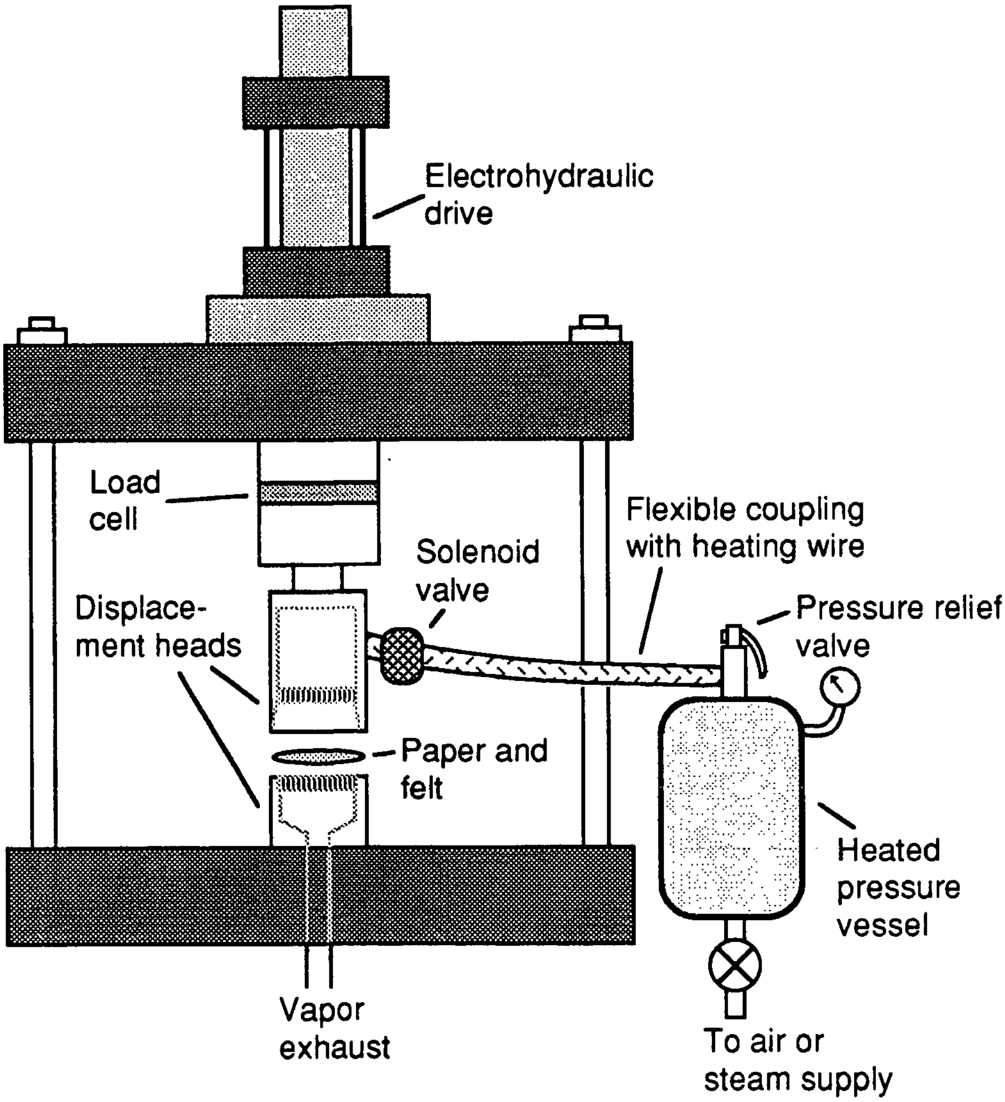

Figure 7. The experimental displacement apparatus.

sion. Carbon paper imprints between the platens were used to check head alignment in order to get a uniform applied pressure.

For displacement dewatering of paper, a 3-in (0.076 m) handsheet disk is placed on a 3-in felt. A fine, stiff disk of either a plastic forming fabric or copper mesh is placed on top of the paper to help distribute the gas pressure uniformly over the paper and to prevent embossing the paper with the pattern of the drilled upper plate. A felt could also be used. Tests have indicated that the gas pressure is

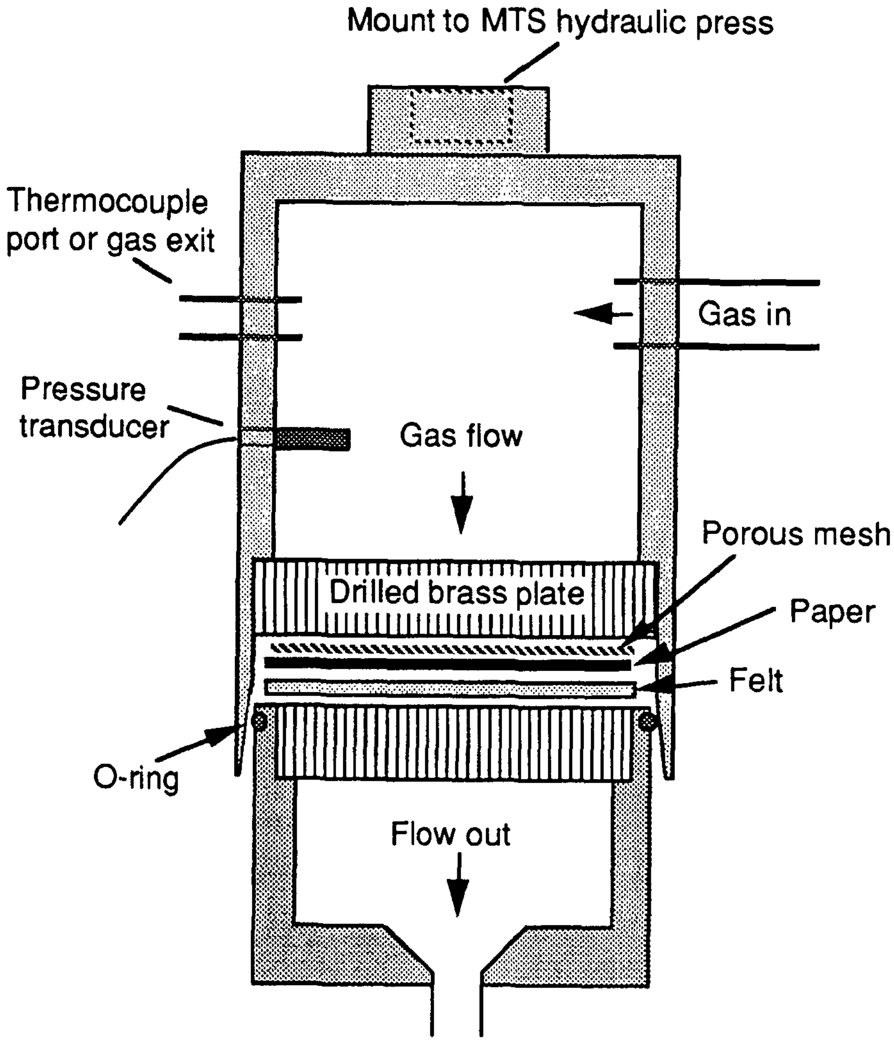

Figure 8. Detail of the displacement heads.

applied evenly to the paper in the tests of this study. The fabric-paper-felt stack is placed on the lower drilled plate. An electronic switch then drives the upper head downward to apply a controlled pressure pulse typically lasting for 20-100 ms. As the mechanical pressure pulse begins, a relay opens the solenoid valve for a specified time and the pressurized gas then fills the upper chamber and begins to assist the dewatering of the paper. Gas pressures of 20-110 psi have been used.

Unfortunately, the fastest solenoid valve which could be purchased still had a lag time of about 20 ms before the valve is fully open. Once the valve is open, the chamber reaches full pressure in about 5 milliseconds. A control system was thus devised which could trigger the solenoid valve within a range of over 100 ms before sheet compression begins to over 100 ms after compression ends. Generally the solenoid was fired 10-20 ms before the beginning of the mechanical pressure pulse, providing a gas pulse to the sheet that began only after substantial compression had occurred.

The new displacement heads overcame the problem of nonuniform gas pressure by providing a large chamber above the sheet to allow the applied gas pressure to become spatially uniform during displacement. An O-ring assembly prevented gas leakage from the upper chamber during displacement.

"Unconfined" Displacement Dewatering

The greatest difficulty with the new equipment, which also appears to have been a problem with the previous equipment used for this project, was controlling the duration of the applied gas pressure. We wished to release the gas pressure before the expansion phase of the press event began; this would keep the gas application time low and prevent significant blowing as the sheet decompresses and becomes more permeable. (Blow through should not harm the sheet and will increase the dryness by water entrainment and evaporative drying, but we wished to avoid significant air flows through the sheet.) Controlling the gas pressure proved problematic, however. We attempted to use a second fast-acting solenoid valve on the upper head to release the gas at a specified time. Unfortunately, even the best solenoids that we could locate did not perform as required. Solenoid valves require upstream pressure or flow to become properly seated; the sudden burst of pressure as the first solenoid opened blew open the second solenoid before it could seat, releasing the vapor pressure.

The first set of experiments was thus run with only one solenoid valve. The port which had served as the exit port to the second solenoid valve was sealed, and the applied gas remained pressurized until it either passed through the sheet or was released as the two displacement heads separated (usually a combination of both). As a result, the vapor pressure duration in the first set of experiments was undesirably long, ranging from 100 to 350 ms, and exceeded the duration of the mechanical pressure pulse. Since the gas pulse was not confined within the time of the mechanical pressure, these runs are termed *"unconfined"* displacement dewatering. Figure 9 shows pressure pulses during a typical unconfined run.

The long gas pulse in the unconfined runs allowed us to test the upper limits of the displacement process: if the process appears economically inviable at these conditions, there is no reason to explore it at shorter durations.

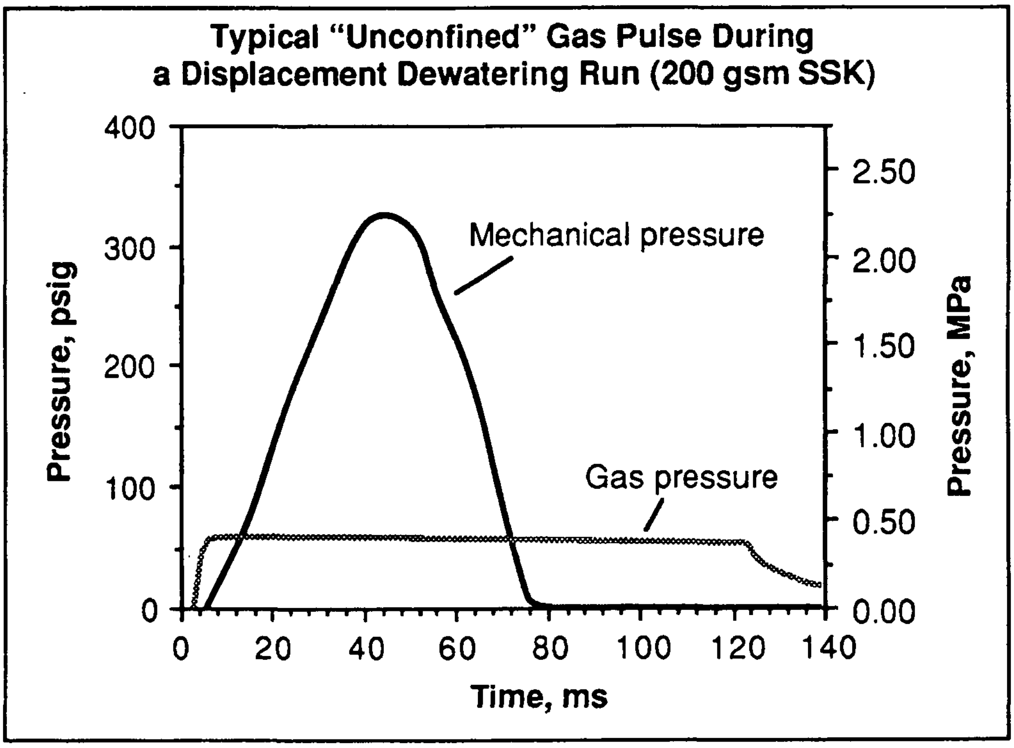

Figure 9. Applied gas and mechanical pressure pulses during a typical "unconfined" displacement dewatering run. The gas pulse is not confined within the mechanical pressure pulse, but extends well beyond.

"Confined" Displacement Dewatering

Following the somewhat favorable results of the first series, a second series of experiments was launched in which the duration of vapor displacement was made shorter by leaving an opening in the gas exit/thermocouple port of the upper head. The open time of the inlet solenoid was also shortened as much as possible (too short a signal would lead to closing before the solenoid was fully open). With this arrangement, a series of tests with more desirable gas pulses could be achieved. Figure 10 shows the typical gas and mechanical pressure pulses for such a run. Since most or all of the gas pulse is confined within the mechanical pressure pulse, these runs are termed "confined" displacement dewatering.

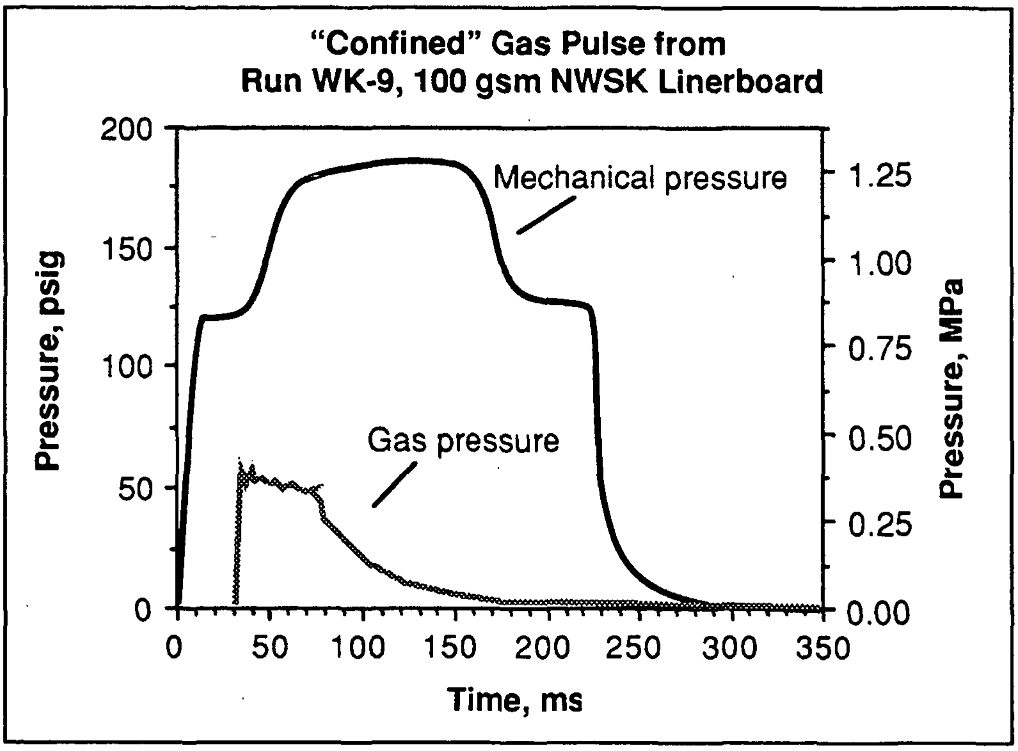

Figure 10. Applied gas and mechanical pressure pulses during a typical "confined" displacement dewatering run.

Run Procedures and Conditions

Displacement dewatering and wet pressing runs were made in a variety of handsheets, primarily linerboard grades. The two main linerboard furnishes were a Northwestern softwood unbleached kraft (NWSK) and a Southern softwood unbleached kraft (SSK). Both furnishes had freeness levels of about 700 CSF. Some runs were made in handsheets from an unbleached thermomechanical pulp (TMP). The TMP had a freeness of about 100 CSF. Saturated 240 gsm commercial blotter paper was also used as an example of a heavy but highly permeable material.

In each run, a wet sheet was weighed, then placed between a dry felt and the fine plastic or copper mesh, and the assembly was set on the drilled bronze plate of the lower displacement head. The MTS control system was activated, which would cause the pressing and displacement event to occur. As the upper head retracted, the sheet was removed and weighed again. The sheet was then dried at about 100°C under mild constraint, and its thickness was measured at 4-10 random sheet locations to obtain an average. From this information the solids in, solids out, and sheet density could be determined.

Displacement was done with both room temperature air and superheated steam. When steam was used, the pressure vessel and the flexible coupling to the upper displacement head were heated and insulated. The pressure vessel was heated with a band heater near the centerline, and temperatures measured there were typically 315-330°C. The heated flexible coupling to the solenoid valve was at about 175°C. The temperature inside the upper head just prior to displacement was 120-150°C, achieved by passing some pressurized steam through the head while compressing a disk of blotter paper on a felt. This head temperature was usually sufficient to prevent significant condensation in the head during a displacement event. Without this preheating of the head, condensate drops would often be found on sheet after displacement.

The use of steam posed a number of problems. While condensation was prevented by heating the displacement head, the MTS system also warmed up.

This often played havoc with the dynamic response of the system. The solenoid valve, rated for high temperatures, also tended to behave erratically with steam, frequently misfiring. A number of good runs were possible with steam, however.

The peak mechanical pressures in the displacement runs ranged from 180 to 400 psi (1.2-2.8 MPa), well below what is typically used in wet pressing. Nip residence times were large, however, with a range of about 70-300 ms. The lower limit is due both to control problems encountered in the MTS at low mechanical pressures, and the dynamic limits in the gas application system.

The applied gas and mechanical pressure pulses were measured with a load cell and pressure transducer, respectively, and monitored with an oscilloscope. Digital readings of peak mechanical pressure and total pressing impulse were available.

Wet Pressing Variants: Normal, Low Pressure, and Open Surface

To compare the densification of displacement dewatering with the densification of conventional pressing operations, we wished to press a number of sheets without any gas being applied. If displacement dewatering is done in the normal manner, but with gas at zero or very low pressure, the pressing efficiency is low. In such a pressing event, termed "open-surface wet pressing," the sheet is pressed by an open wire surface backed with an open drilled platen. (In Figure 5, for example, the data labeled "without air" represent open surface wet pressing.) Without significant gas pressure being applied, water may pool above the sheet and cause rewetting, or sufficient hydraulic pressure for dewatering may not be generated. The low dryness levels achieved in this manner are an artifact of the experimental setup, and would be different if another gas delivery and distribution system were used, such as a porous platen composed of sintered metal without a layer of wire or fabric on the paper. Comparison of displacement dewatering to open-surface wet pressing is an inappropriate means of evaluating process performance.

To create a true wet pressing effect, the pressing surface of the sheet must be solid. By replacing the wire mesh with a rigid disk of acrylic plastic, wet pressing could be simulated in the displacement apparatus. Gas was not applied, of course, during such runs. During a series of displacement dewatering runs, occasional wet pressing results would be obtained using this method. The wet pressed sheets were thus subject to essentially the same mechanical pressure pulse as was used in the displacement dewatering tests of that particular run. Because the peak mechanical pressures were lower in these runs than is typically used in commercial wet pressing, this method of wet pressing is termed "low-pressure wet pressing." In the industrial practice of wet pressing, it is commonly noted that wet pressing density-dryness data tend to fall on the same curve, regardless of the details of the wet press operation. Therefore, during most of this study, it was simply assumed that the density-dryness data for a given sheet type obtained with low-pressure wet pressing would fall on the same curve as similar data sets obtained under different wet pressing conditions. This assumption was finally tested by obtaining "normal wet pressing" data.

"Normal wet pressing" in this study refers to wet pressing data obtained by pressing paper on a felt between solid platens using mechanical pressures from about 300-1200 psi and nip residence times of 20-50 ms. The applied mechanical pressures are higher and the nip residence times much lower in "normal wet pressing" than those used in the low-pressure wet pressing tests, and are closer to the conditions used in commercial operations.

RESULTS

Water Removal and Densification

Unconfined Displacement

The unconfined tests were run to check the upper limits of displacement dewatering. Being "unconfined," the gas exposure times were longer than the nip residence times, with total gas exposures on the order of 350 ms. Peak mechanical pressures were about 340 psi. The results from this series gave positive indications that displacement dewatering could effectively remove water, and did not serve to disprove the concept. To further test the concept, it was necessary to run tests under the more critical confined conditions. Since the confined displacement results provide the most useful data for evaluating the proposed process, they will be emphasized in this paper.

One key set of data from the unconfined series with superheated steam is given in Figure 11, where density-dryness relationships for three batches of 100 gsm handsheets are examined. Two batches of sheets were made from a Southern softwood unbleached kraft (SSK) furnish, and the other was from unbleached TMP. Most runs employed an 80 ms nip residence time, although in SSK batch 1, times up to 200 ms were used. Steam exposure times were on the order of 100-150 ms longer than the nip residence time. The enclosed shaded area contains the low pressure wet pressing results (same mechanical pressure pulses as the displacement runs, with a solid surface in contact with the upper sheet surface), and the other data points give the steam displacement results.

The two linerboard batches give consistent results, indicating that lower densities are achieved than is possible with low-pressure wet pressing, and also indicating that high dryness levels can be achieved. Even more encouraging are the TMP steam results, where the density-dryness curve is flat. This suggests that high solids levels can be achieved with no significant losses in bulk. However, given the long exposure times of unconfined displacement, these results were probably achieved largely by thermally drying the sheet with steam rather than by displacing the liquid water. An energy balance has not been done, but this particular process is not likely to save energy costs. To more realistically explore the potential of displacement dewatering, we must consider results with confined displacement, where shorter gas exposure times are used and less gas is wasted by blowing through the sheet after the end of the nip.

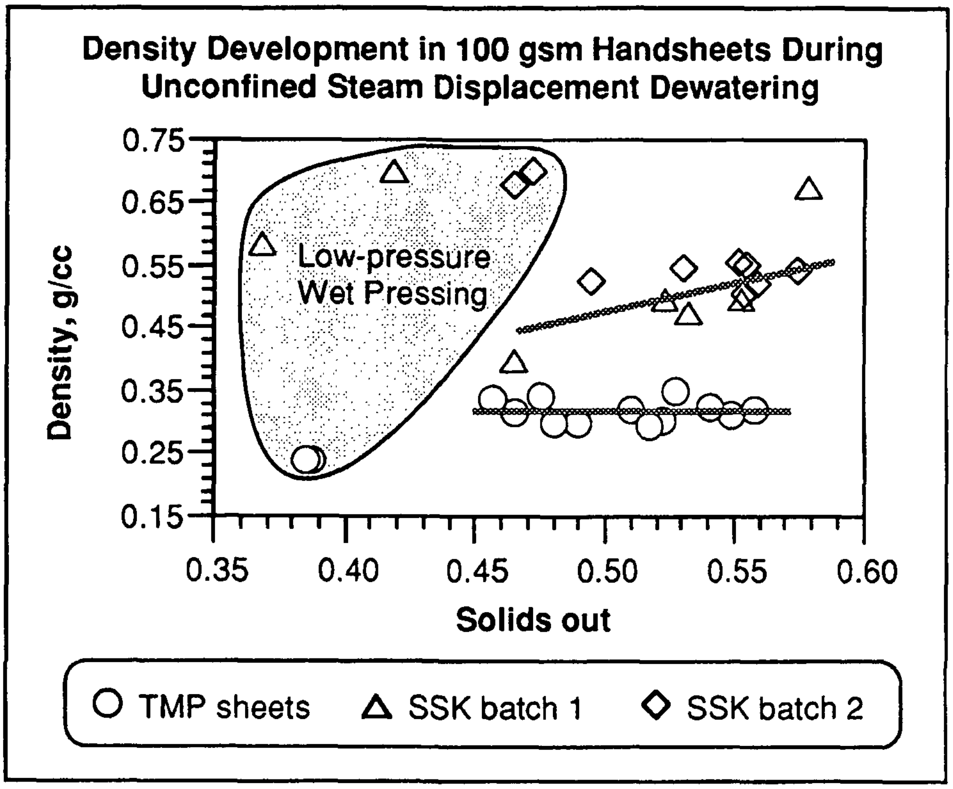

Figure 11. Density-dryness relationship for unconfined displacement dewatering with superheated steam.

Low Pressure, Confined Displacement

In the confined displacement runs, the equipment and the MTS/solenoid valve dynamics were adjusted to ensure that most or all of the gas pressure was contained within the duration of the mechanical pressure pulse (see the discussion in the experimental section above). Low mechanical pressures were used, ranging from 180-300 psi peak pressure (1.2-2.1 MPa peak).

Saturated blotter paper was examined first in the confined displacement series. The data for air displacement in blotter paper are shown in Figure 12. Displacement dewatering yields higher solids levels than low-pressure wet pressing at the same press conditions, but low-pressure wet pressing at a moderately higher pressure (2.34 MPa or 340 psi peak) produces about the same dryness that was achieved with 80 psi (0.55 MPa) of air. Density effects were not considered in the blotter paper, which had already been dried prior to being saturated for this experiment (it was felt that the results would not be of any real value).

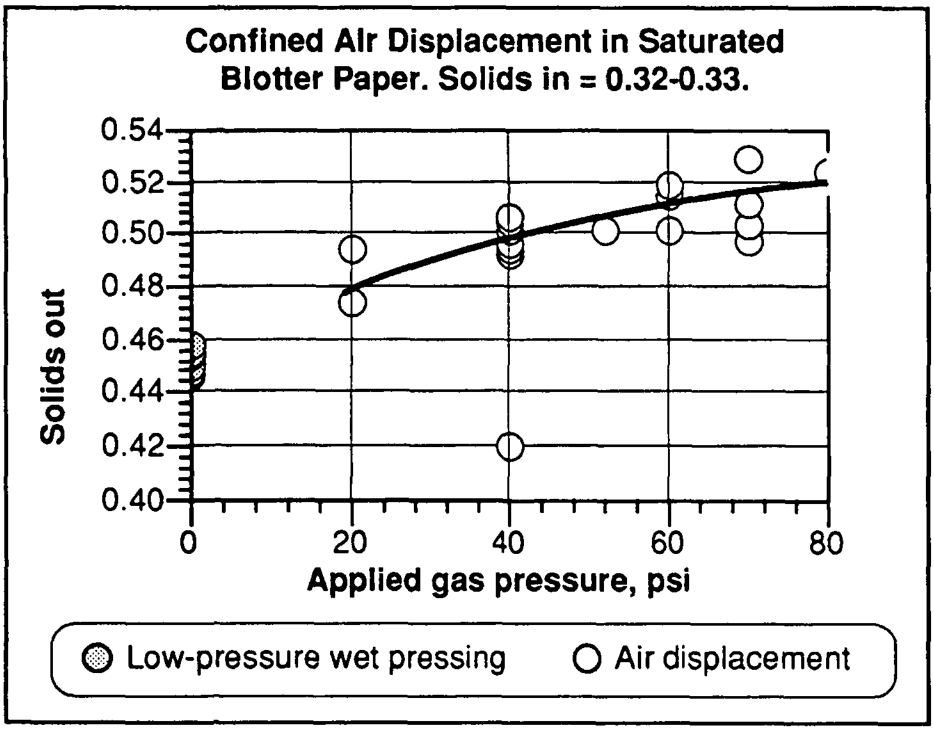

Figure 12. Air displacement results in saturated blotter paper.

More meaningful runs were then done with freshly made linerboard handsheets in order to examine the issue of bulk control with confined displacement dewatering. In particular, it was desired to not only compare displacement dewatering with low-pressure wet pressing under similar press conditions, but also to compare the results with normal wet pressing (done under conditions more closely related to commercial pressing, as described above).

The linerboard handsheets were made from the Northwestern softwood unbleached kraft (NWSK) furnish. First, normal wet pressing data were obtained. A variety of nip residence times and peak pressures were used to obtain a range of dryness values. Peak pressures up to 1200 psi were achieved, with residence times on the order of 20 -60 ms. This was done for 100 and 150 gsm NWSK sheets. The results are given in Figure 13. Both basis weights show similar behavior.

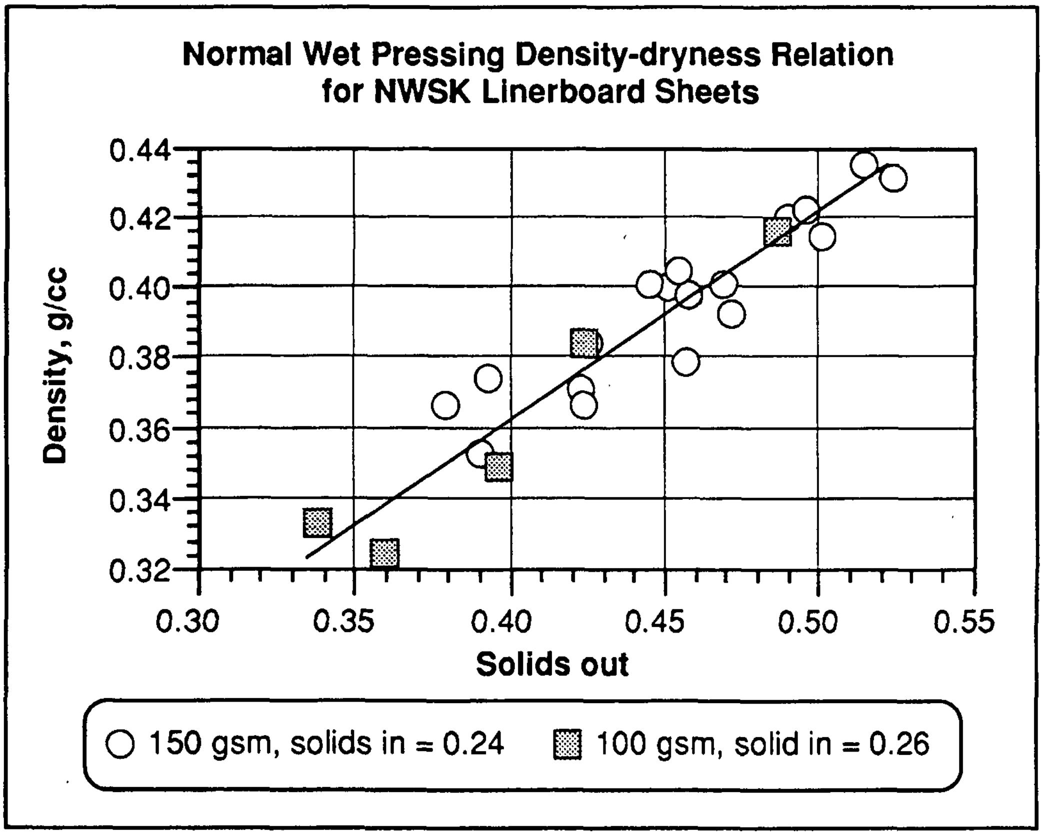

Figure 13. Dryness-density relationship for normal wet pressing in Northwestern softwood unbleached kraft (NWSK) handsheets.

Air displacement was then examined in 150 gsm sheets of this furnish. Nip residence times ranged from 120-140 ms, with peak pressures of about 340 psi (2.3 MPa). Peak gas pressures lasted for 60 ms and total gas exposure time (gas over

10 psi or 0.07 MPa) was 120 ms. The results, shown in Figure 14, were not encouraging. At 80 psi (0.55 MPa) only a 5% gain in solids was possible over low-pressure wet pressing under the same pressing conditions (including, of course, the long nip residence time). When the density-dryness data were examined, a disturbing result was found. As can be seen in Figure 15, displacement dewatering gives lower density at a given solids than low pressure wet pressing, but compared to the previously collected normal wet pressing data (Figure 13), there is a substantial increase in density. The assumption of a single density-dryness curve for wet pressing is clearly incorrect in this case. Perhaps the long nip residence times (225-240 msec) used in the displacement runs and low-pressure wet pressing runs caused a loss of springback through a creep effect and thus yielded higher density, even though lower mechanical pressures were applied.

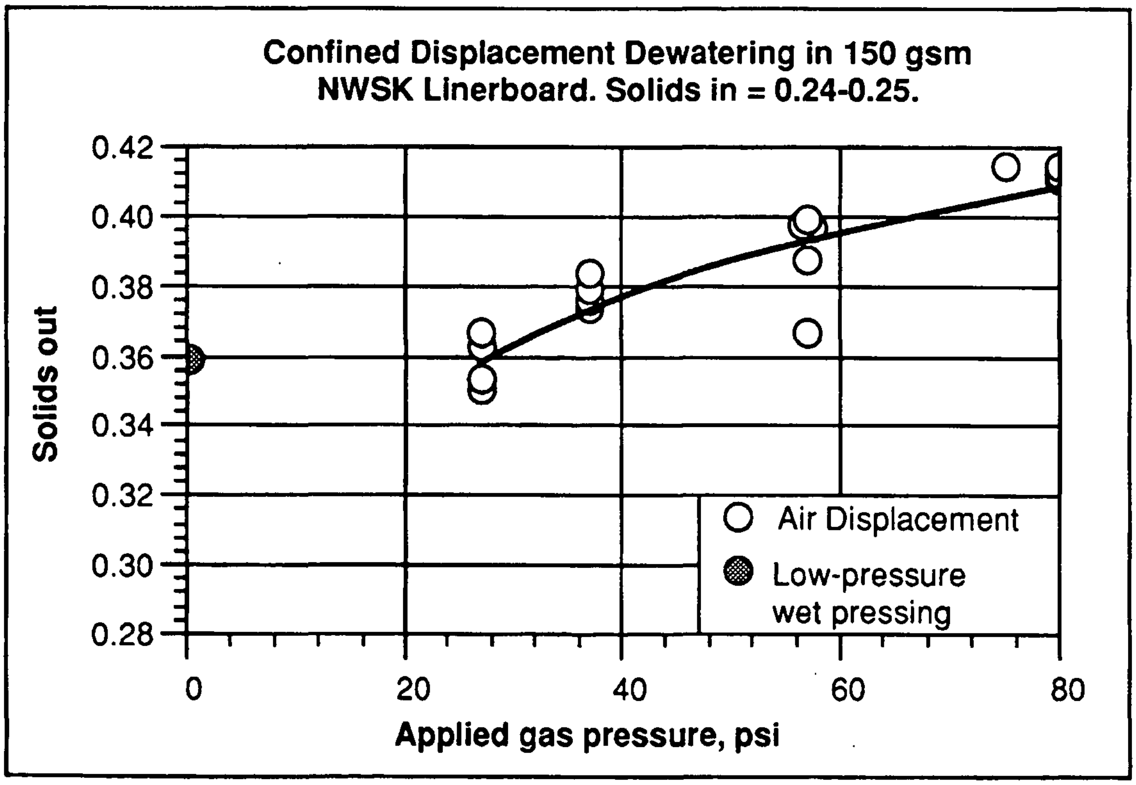

Figure 14. Confined air displacement in 150 gsm NWSK sheets.

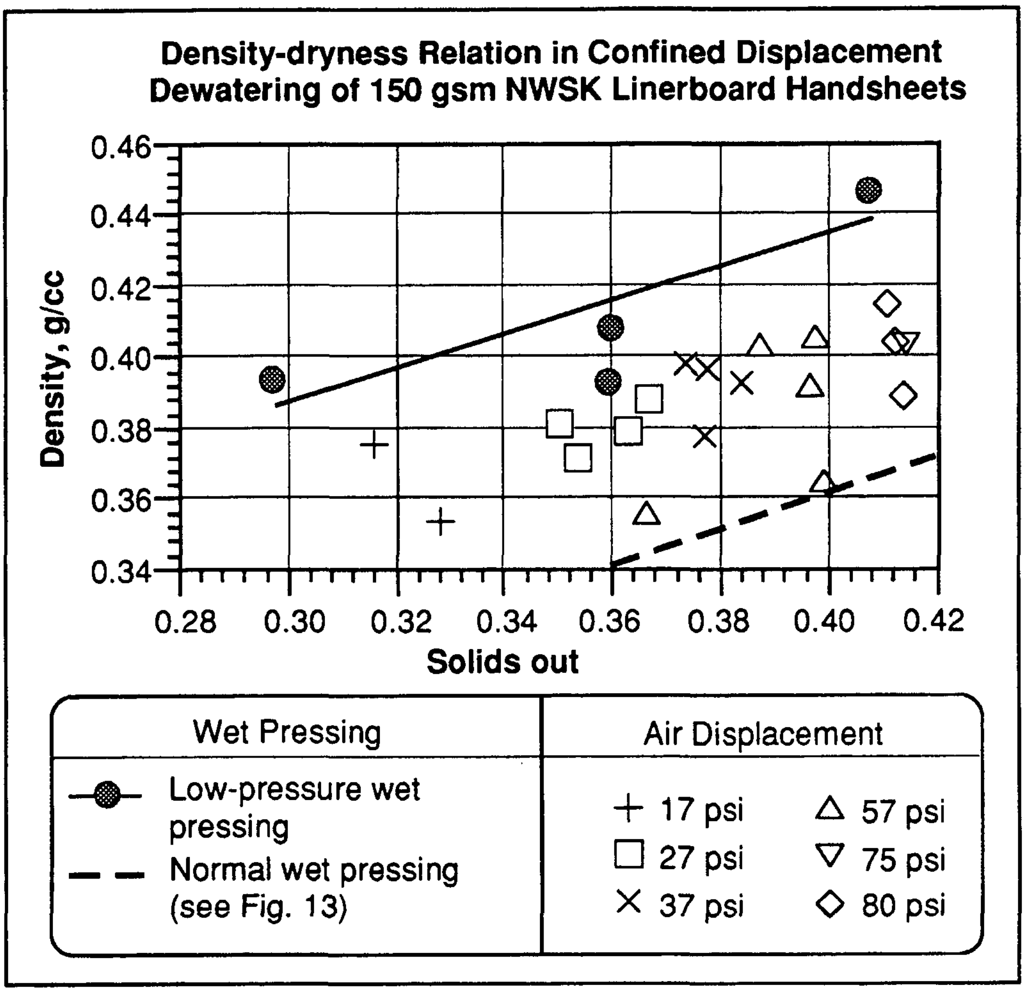

Figure 15. Density-dryness relation for data of Figure 14.

Similar runs were then conducted for 100 gsm NWSK linerboard sheets. Mechanical pressures ranged from 150 to 240 ms, and lower mechanical pressures were used, with peaks of 180-200 psi (1.2-1.4 MPa). Gas exposure times were still at 120 ms, with gas peak pressures lasting for 50-70 ms. In addition to air displacement, superheated steam was also used. The dewatering results for both air and steam displacement are shown in Figure 16, and density information is given in Figure 17. With such low mechanical pressure, low-pressure wet pressing alone raised the solids level from 0.25 to just 0.28. Air displacement was more effective, but the gains are not impressive. Steam dewatering again shows more promise, with over 44% solids possible. The density data, however, are not encouraging. Steam displacement seems to significantly increase the densification of the sheet, probably by thermally softening the sheet and decreasing its resistance to compression. And while the air displacement process gives better bulk than an equivalent wet pressing operation, wet pressing in a shorter nip (see the data in Figure 13 above) gives about the same density-dryness curve. Some of the displacement data points lie below the short-nip wet pressing curve, indicating that some decoupling of dryness and density may be possible under these conditions, but the effect may also be due to scatter in the data.

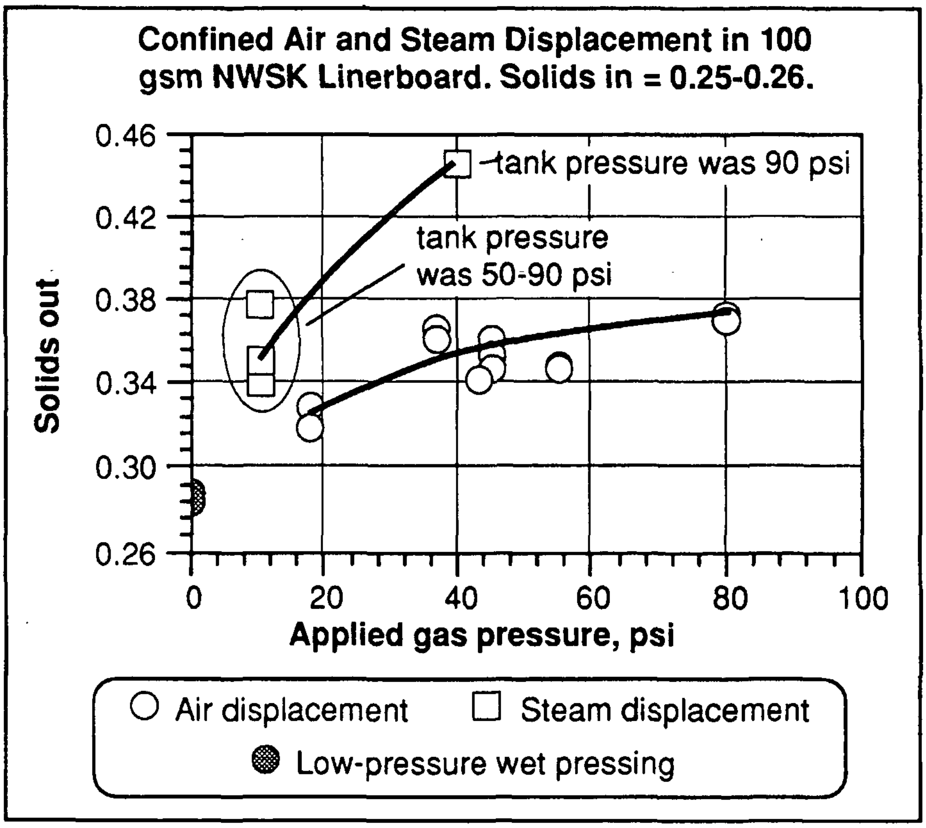

Figure 16. Steam and air displacement in 100 gsm NWSK sheets. Peak mechanical pressures were 180-200 psi.

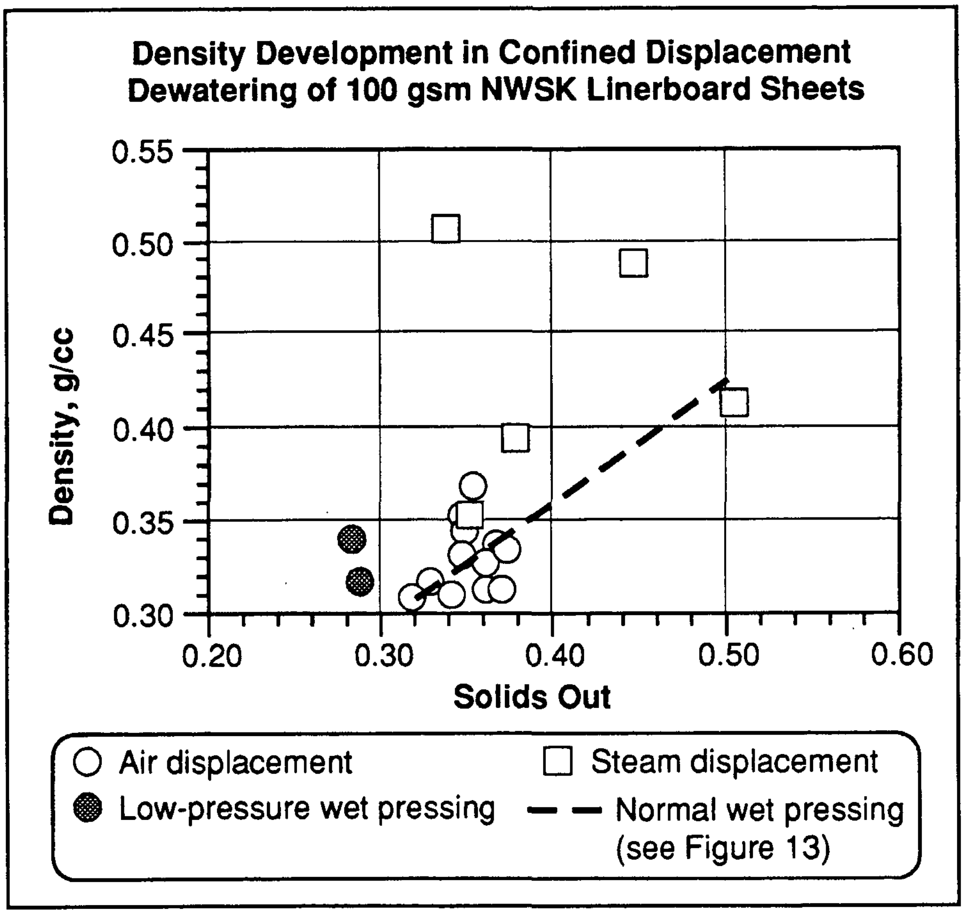

Figure 17. Density-dryness relationship in steam and air displacement dewatering of 100 gsm NWSK sheets.

Blow Through During Confined Displacement Dewatering

Since gas was primarily applied only while the sheet was under significant compression in the confined series, the resistance to gas flow was high and blow through was relatively low. However, some gas still blew through the sheet. Measurements made during runs with 150 gsm linerboard sheets and 60 psi of air suggested that 0.5-0.8 liters of air at atmospheric pressure were passing into the lower MTS head during a 120 ms pulse of "confined" gas pressure. Not all of this gas had to pass through the sheet, for edge flow around the sheet and through the felt may have been significant. Nevertheless, it is likely that channeling or viscous fingering occurs quickly and permits gas to flow through the sheet. This is in stark contrast to the ideal of displacement dewatering, namely, that the amount of gas required is the minute amount corresponding to the volume of the water being displaced.

Experimental Artifacts at Low Gas Pressures

In the figures above, results from open surface pressing have not been included because such a pressing operation has little relevance to practical water removal. The low dryness levels achieved are an artifact of the experimental setup. A similar artifact occurs when displacement dewatering is attempted with gas at too low a pressure to overcome the adverse effect of using an open pressing surface. In that case, often observed with pressures below 25-30 psi (ca. 0.2 MPa), displacement dewatering appears to give worse results than low-pressure wet pressing with the same nip conditions. For example, Figure 18 shows the full air displacement data set from which Figure 14 above was created. Low-gas pressure displacement data are included here which were discarded in Figure 14 for clarity (i.e., it was desired to save presentation and discussion of low pressure artifacts for later). As Figure 18 shows, over 30 psi (0.2 MPa) was required to overcome the adverse effect of an open upper platen. The "post-nip gas pulse" datum refers to a run in which the solenoid valve did not open until after paper had been pressed. This data point indicates the relative ineffectiveness of applying the gas phase when the sheet is not under a mechanical load.

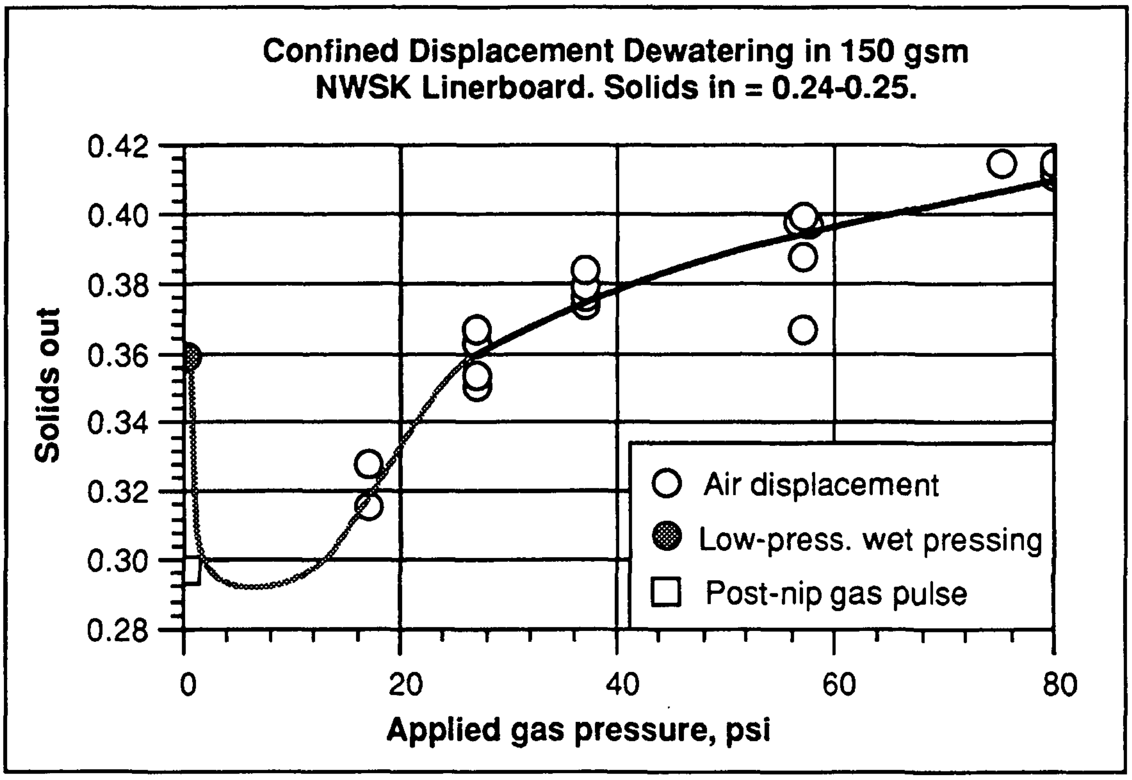

Figure 18. Confined air displacement in 150 gsm NWSK sheets.

Data for confined air displacement in blotter paper, previously shown in Figure 12, are again shown in Figure 19, but now with the full data set from that run. Displacement pressing at low gas pressure is worse than similar low-pressure wet pressing because of the lower hydraulic pressures generated under the open holes of the drilled bronze plate. Figure 19 also includes data points for cases when the gas pulse was fired after the paper had been largely decompressed, but the seal between the upper and lower heads was still intact. These are shown at 0 psi since no gas was applied during the bulk of the mechanical pressure pulse. Such data again show the losses in dewatering when the sheet is not under sufficient mechanical pressure. Two data points are also shown from displacement runs where the solenoid valve failed to open, resulting in open surface wet pressing. The low dewatering (37% solids out) compared to regular wet pressing data (45% solid out) shows the adverse effect of pressing without a solid surface over the sheet.

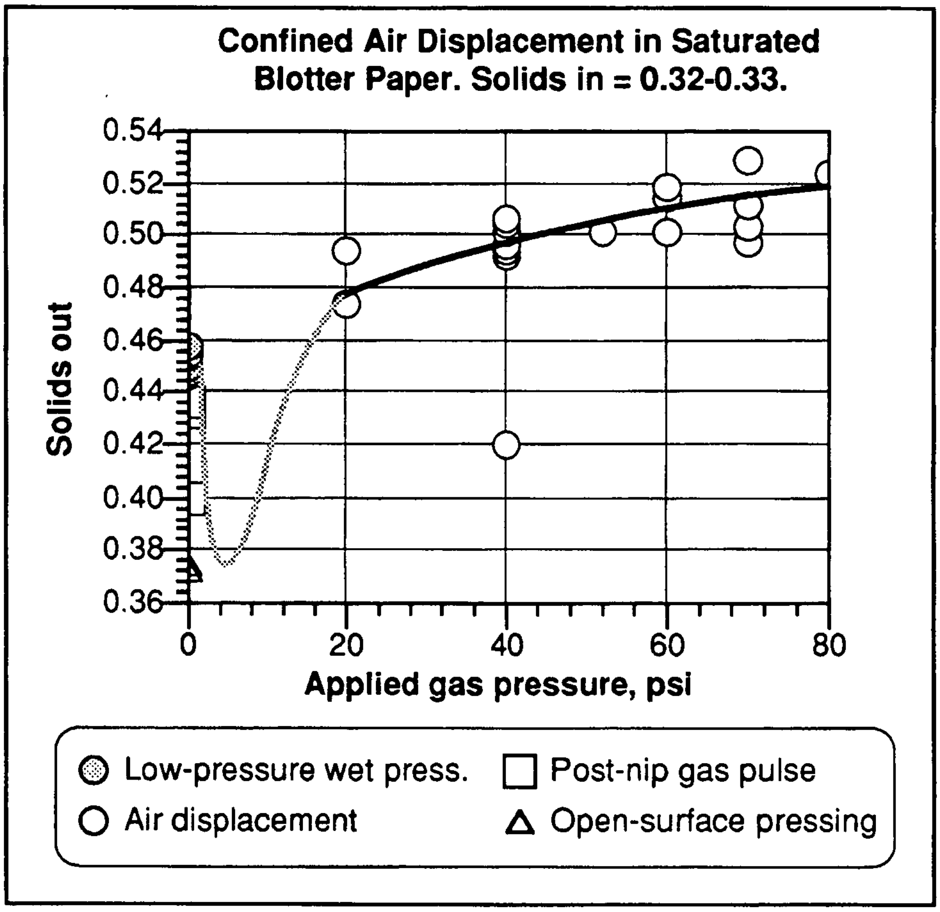

Figure 19. Full data set of air displacement results in saturated blotter paper (partially shown in Figure 12).

DISCUSSION

Improvements in Bulk?

In evaluating the commercial potential of displacement dewatering, we must focus on the ability to give added control over paper properties, with bulk or sheet density being most critical. The degree of water removal is also important. Both can be discussed in terms of density-dryness results.

Based on simple theoretical considerations, improved control over bulk should be easily achieved and has been the primary motivation for this study. The potential to control bulk is best examined by comparing density-dryness data for displacement dewatering and wet pressing. Several pitfalls arise, however, in making this comparison. If displacement pressing is compared to "wet pressing" done in the same way but without any gas (i.e., open-surface wet pressing, as defined above), the results can be impressive. Much higher dryness levels are achieved with no significant loss in bulk. But this is not a proper comparison because of the adverse effect of wet pressing without a solid platen in contact with the sheet.

A more logical evaluation can be made by comparing displacement dewatering with wet pressing (no gas) done under the same press conditions, but now with a solid surface replacing the wire or mesh to generate a wet pressing event. While this is termed low-pressure wet pressing because of the low mechanical pressures that were applied, the long nip residence times used should also be kept in mind. Compared to low-pressure wet pressing, displacement dewatering gives improved water removal once a certain gas pressure threshold is reached (ca. 30 psi in this study). Higher bulk levels for a given solids content can usually be achieved, and the process thus appears to have promise.

However, the pressing conditions of displacement dewatering are much different than what is used in conventional wet pressing, especially since the nip residence time is extremely long. When "normal" wet pressing is done with shorter times and higher pressures, a different density-dryness curve is obtained. The normal wet pressing density-dryness curve lies below the low-pressure wet pressing curve and is below much of the displacement dewatering data. In other words, displacement dewatering may give worse bulk levels than normal wet pressing, possibly because of creep effects drastically reducing the springback of paper during the long nip. The problem may be exacerbated with steam where thermal softening of the fibers leads to higher compression.

Nevertheless, by using the proper combinations of nip residence time, gas pressure and gas exposure time, the problem with excessive densification may be overcome, and the concept of displacement dewatering may prove viable. Further work is clearly required, and is now underway.

Inherent Inefficiency

The classical concept of viscous fingering during gas-liquid displacement in porous media may underpredict the problems faced in displacement dewatering. The theory of viscous fingering is based on the concept of a homogeneous porous medium, meaning that for the length scales of interest in the problem, the medium can be treated as a single substance, a smooth blend of solid and void volumes. In such a system a flat interface between two phases during displacement could exist and could propagate without change were it not for unfavorable viscosity ratios. But in a thin structure like paper, where the solid elements are not tremendously smaller than the sheet thickness, the concept of homogeneity becomes inapplicable. Instead, we must realize that there will be some large, easily emptied pores and many small or blocked pores through which displacement cannot occur. As a result, the displacement process considered here is bound to be less efficient than theory would predict. Blow through may always occur under practical conditions. (See Brundrett and Baines [30] for a good discussion of the flow of air through uncompressed but wet sheets.) The mechanism of water removal in "displacement dewatering" is thus likely to be a combination of displacement, entrainment, evaporative through-drying, and rewet resistance. The latter mechanism has been discussed in the context of impulse drying (20), and is likely to apply here: sustained gas pressures existing in the sheet during nip expansion can continue driving water into the felt, resisting any back flows from the felt into the sheet. The importance of rewet resistance, however, has not yet been experimentally confirmed.

CONCLUSION

The concept of simultaneous gas and mechanical pressure to displace water from paper has been tested under several conditions and with several sheet types. The displacement dewatering concept requires further testing, but has not yet been found to dewater efficiently while preserving bulk. Use of air as a displacing medium did not give substantial dryness gains over what can be achieved with wet pressing. Displacement dewatering with superheated steam can give high dryness levels, but the effect is probably due to evaporation rather than displacement. Steam displacement can also seriously decrease bulk levels by thermal softening of the sheet under compression.

It is too early to discard the displacement dewatering concept, but there are a number of serious obstacles to overcome. The formidable engineering task of implementing a displacement process in a paper machine was once viewed with great concern, but the most serious obstacle now is finding a bench-scale process that achieves the objective of efficient water removal with control over bulk.

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