

Deinking flexographic newsprint: using ultrafiltration to close the water loop

BRADLEY H. UPTON, GOPAL A. KRISHNAGOPALAN, AND SAID ABUBAKR

THE MOST COMMON PRINTING techniques for the production of newspapers are letterpress and lithography (offset). Flexographic printing has recently been applied to newsprint publication and holds several advantages over letterpress and lithographic printing (1, 2). The primary disadvantages of flexographic newsprint publication are the difficulties associated with recycling due to the water-dispersible flexographic inks. Conventional flotation technology is widely used for deinking secondary fiber furnish that has been printed by the letterpress or lithographic (offset) processes, but it is ineffective in removing flexographic ink residues (3-6), which form fine dispersions of pigment particles upon alkaline pulping (7). The same properties of flexographic ink dispersions that render them difficult to remove by flotation deinking, specifically colloidal dimensions and hydrophilic surfaces, lend them to efficient removal by washing techniques (8-10). The wash filtrate from deinking newspapers printed with flexographic ink is estimated to contain between 0.05% and 0.1% pigment. These pigments must be removed before this stream can be recycled to the process without decreasing pulp brightness.

Operating under acidic, or at least nonalkaline conditions, improves the efficiency of froth flotation in removing water-based flexographic inks. A two-stage process consisting of nonalkaline flotation

for removal of flexographic inks, followed by alkaline flotation for oil-based ink removal, has been proposed (2). There is also interest in developing flocculation aids (polymers) capable of rendering flexographic pigment particles hydrophobic (7), which would result in an increased tendency for the flexographic inks to be removed by conventional alkaline flotation deinking. Membrane separation technology is a potentially attractive method for the removal of flexographic ink residues from wash filtrate without further addition of chemicals (11). Deinking a mixed old newsprint furnish would rely on both froth flotation and washing, with the wash filtrate clarified by ultrafiltration before being recycled to the process.

Ultrafiltration removes contaminants based on size. Most modern membrane separation processes are operated under "cross-flow" conditions. The membrane is configured in a tubular or hollow fiber geometry, in which the liquid to be clarified flows axially through the interior of the tube under pressure. The pressure forces any permeable materials to pass through the membrane. This permeate consists primarily of solvent and contains some dissolved or suspended materials, depending on the membrane pore size. Larger solutes and solids are retained in the feed stream. The permeation rate of fluid through the membrane is reported as flux, with units of volume per unit of membrane surface area per unit time ($L/m^2 \text{ h}$). The axial

RECYCLING

ABSTRACT

Conventional flotation deinking technology is widely used for deinking secondary fiber furnish that has been printed by the letterpress or lithographic (offset) processes. This technology is not effective for removing water-based flexographic inks due to the hydrophilic nature of their pigment particles. Washing effectively removes flexographic ink dispersions from pulped secondary fiber; however, the resulting wash effluent contains significant quantities of pigment. The wash effluent must be clarified of pigment before it can be recycled within the mill without reducing pulp brightness. The difficulty in clarifying flexographic pigment dispersions from wash filtrate represents a significant barrier to closing the water loop of a newsprint deinking operation.

Ultrafiltration was investigated as a means to remove dispersed water-based ink pigments from wash effluent. Ultrafiltration of high-concentration ink dispersions resulted in stable, high production rates of pigment-free permeate. The use of high-concentration feeds prevented irreversible membrane fouling and actually demonstrated membrane regenerative properties. Inclusion of cellulose fines in the feed had variable effects on permeation rates.

Application:

This research investigates the applicability of ultrafiltration to clarify water-based pigments from process water of an old-newsprint deinking facility. Clarification of the wash water will maximize wash water recycling in the process without affecting pulp color.

flow of fluid through the tube creates a shear stress field parallel to the membrane surface, retarding the accumulation of a thick filter cake.

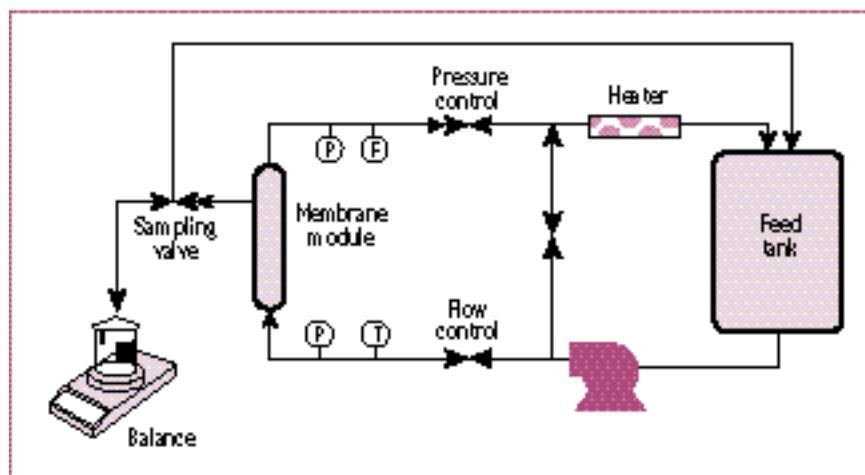
This study focuses on the feasibility of ultrafiltration techniques to

remove hydrophilic pigments from aqueous dispersions. An ultrafiltration apparatus was assembled and used to characterize the clarification of dispersions prepared from two commercially available water-based flexographic inks. The efficiency of the ultrafiltration separation process is characterized by parameters such as permeate flux, fouling rate, and cleaning requirements.

EXPERIMENTAL

The ultrafiltration apparatus was equipped with adequate instrumentation and controls to manipulate pressure drop across the membrane surface (transmembrane pressure, ΔP_{tm} , temperature, and flow rate through the membrane module) (Fig. 1). Two identical polysulfone hollow-fiber ultrafiltration membranes were used. Each membrane module was in a shell and tube configuration with 68 hollow fibers of 0.043 in. (0.109 cm) ID, for a total surface area of 1 ft² (0.0283 m²). The molecular weight cut off (MWCO) is a measure of pore size, or retention ability, and is the approximate molecular weight of the smallest compound retained by the ultrafiltration membrane. The MWCO of the membranes used in this study was 500,000.

Feed solutions were prepared using tap water, flexographic ink, surfactant, and NaOH to adjust the pH to 10. Two formulations of flexographic ink were used, one from a regional newspaper publisher (ink no. 1), and another obtained from an ink manufacturer (ink no. 2). Ink concentrations (C_B) ranged from 0.04% to 22%, as determined by visible light spectroscopy (12). A commercially available anionic and nonionic surfactant mixture was used in an amount necessary to form a 0.01% solution. In some of the experiments, cellulose fines were added to the feed. The fines were generated by beating unprinted newsprint



1. Ultrafiltration apparatus

stock, and the fraction between 65 and 200 mesh was added to the ink dispersions.

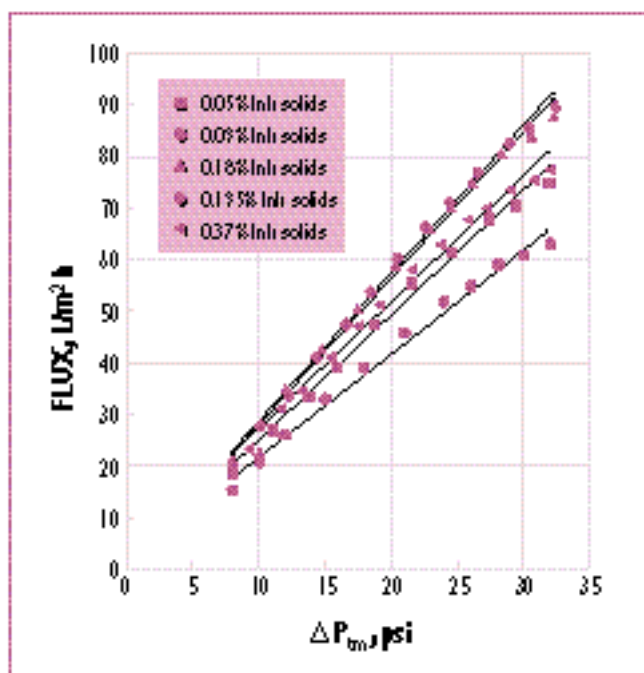
The feed solution was maintained at a constant ink concentration during most of the experiments by recycling the pigment-free permeate back to the feed tank. The permeate was removed from the ultrafiltration loop as it was produced during other experiments, resulting in the ink dispersion becoming more concentrated as ultrafiltration proceeded (the total volume of feed decreased during these experiments). The ink dispersions were kept well mixed by the action of the recirculation pump. In most experiments, the temperature was maintained constant by passing the feed through a constant-temperature water bath. An electric heater was used to heat the feed when performing experiments at elevated temperatures. During these experiments, the water bath was used for fine control of temperature. Flux was measured by the timed collection of permeate in a tared beaker, which rested on a balance. The specific gravity of the permeate was determined to be 1.0. After the flux measurement, the collected permeate was returned to the feed tank.

Immediately following an ultrafiltration experiment the membrane module and entire flow path were rinsed with tap water. A solution of a commercial detergent in tap water (with pH adjusted to 10) was then pumped through the membrane module and associated piping for several minutes. The dirty cleaning liquid was drained from the system, and a fresh cleaning solution was recirculated for at least 30 minutes. The final cleaning was performed using a fresh solution for several hours. At this time the flux was measured at 25 psi ΔP_{tm} , 20°C, and 1 gal/min using a fresh cleaning solution as the feed stream. The resulting value is the water flux, which was used to evaluate the effectiveness of the cleaning procedure on restoring membrane performance.

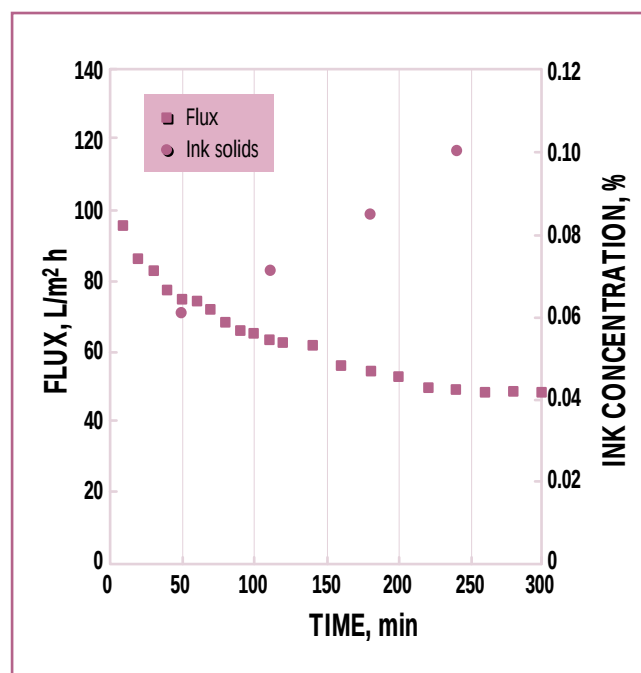
RESULTS

Flux vs. transmembrane pressure

Plots of permeate flux vs. ΔP_{tm} for five dispersions of ink no. 1 are shown in Fig. 2. Ultrafiltration achieved complete retention of the flexographic pigment, producing clear permeate. All dispersions demonstrated linear flux vs. ΔP_{tm} relationships, indicating that the system behaved as predicted by the Hagen-Poiseuille law for streamline



2. Flux vs. ΔP_{tm} ink no. 1



3. Flux and ink concentration vs. time

flow through channels, which is believed to best describe the pressure controlled flow of fluid through microporous membranes (13). The data demonstrate no correlation between ink content of the feed and permeate flux rates. Flux vs. time data for batch ultrafiltration of a 0.05% dispersion of ink no. 1 (25 psi) are shown in Fig. 3. Flux stabilized at 48 L/m² h during the six-hour experiment, while the ink concentration steadily increased from 0.05% to 0.12%, again indicating that flux was independent of solids concentration. Flux vs. ΔP_{tm} data of low-concentration dispersions of ink no. 2 (0.4% and less) also demonstrated pressure controlled permeation; however, at 25 psi flux became less sensitive to further increases in ΔP_{tm} (Fig. 4). The solids content of the feed stream appeared to have a greater influence on flux, which decreased with increasing solids content of the feed stream.

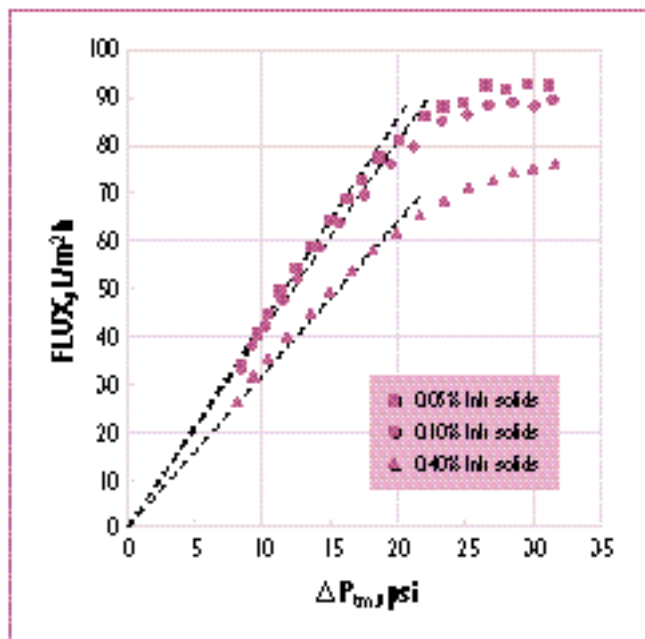
There were two distinct operating regions observed when processing higher-ink-content dispersions

(those at 0.9% ink and above, Fig. 5). Flux was proportional to ΔP_{tm} at low pressure and pressure independent at high pressure. The shift to pressure independence occurred at lower ΔP_{tm} as ink concentration increased, signifying that flux was strongly dependent on solids content. Comparison of the data presented in Figs. 4 and 5 demonstrates that higher flux values were attained while clarifying the high-concentration flexographic ink dispersions than when clarifying the low-concentration dispersions. A discussion of this important finding will follow in later sections.

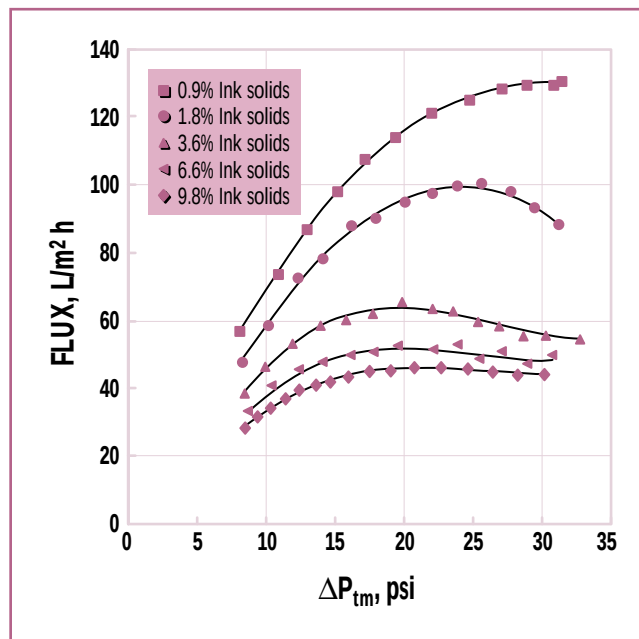
During ultrafiltration of colloidal dispersions, particles are brought to the membrane surface by convective transport as fluid passes through the membrane. This effect is known as concentration polarization. At high flux levels, the nonpermeable material (ink pigment in this case) will consolidate into a "gel layer" on the membrane surface, imparting additional resistance to permeate flow (14-16). Shear forces associated

with fluid flow across the membrane surface control the thickness of this layer, and, at steady state, convective transport and shear force dispersion balance each other (17). This is mass-transfer controlled ultrafiltration, in which flux is pressure independent. Increasing ΔP_{tm} will cause the flux to rise initially, but this will increase the amount of material transported to the membrane surface and thus the gel layer thickness. The flux will then be reduced because of the increased resistance to permeate flow, restoring the equilibrium between pigment transport by convective flow and by shear dispersion. At these conditions, flux is predicted to decrease exponentially with increasing feed concentration (13, 14).

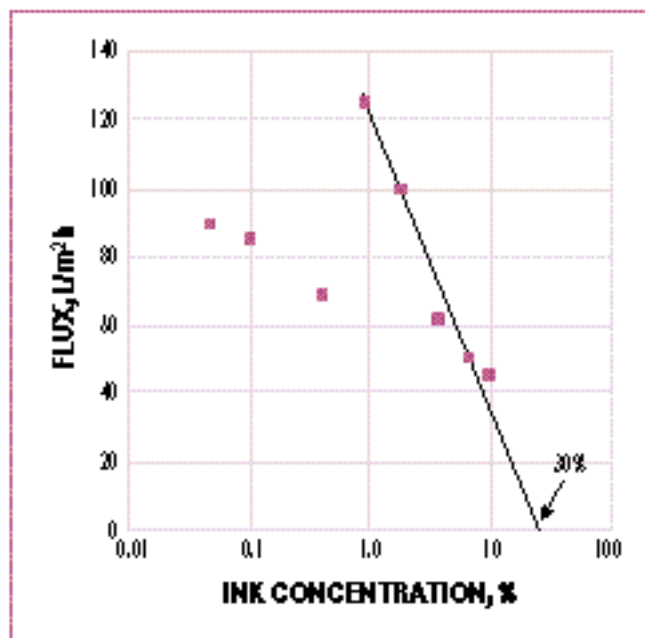
The flux vs. feed composition curve (Fig. 6) demonstrates the logarithmic relationship between flux and ink content observed for dispersions containing 0.9% ink and above (the high-concentration ink dispersions). Porter observed this same trend when ultrafiltering colloidal



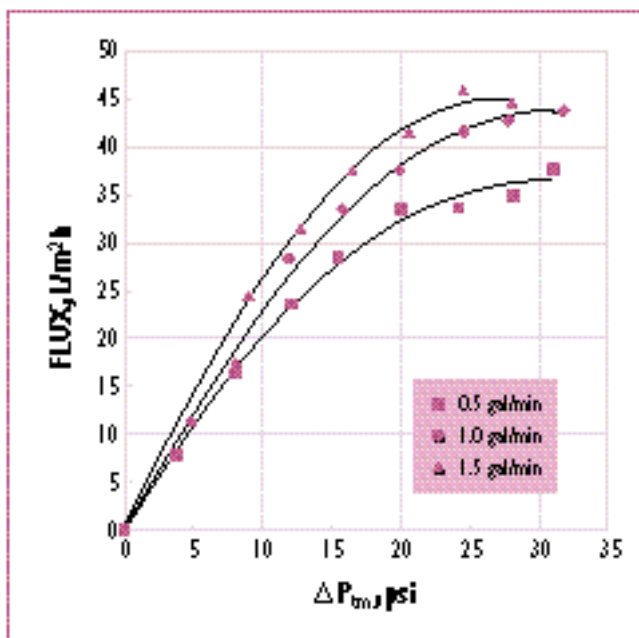
4. Flux vs. ΔP_{tm} low-concentration ink no. 2



5. Flux vs. ΔP_{tm} high-concentration ink no. 2



6. Flux vs. ink concentration at 24 psi



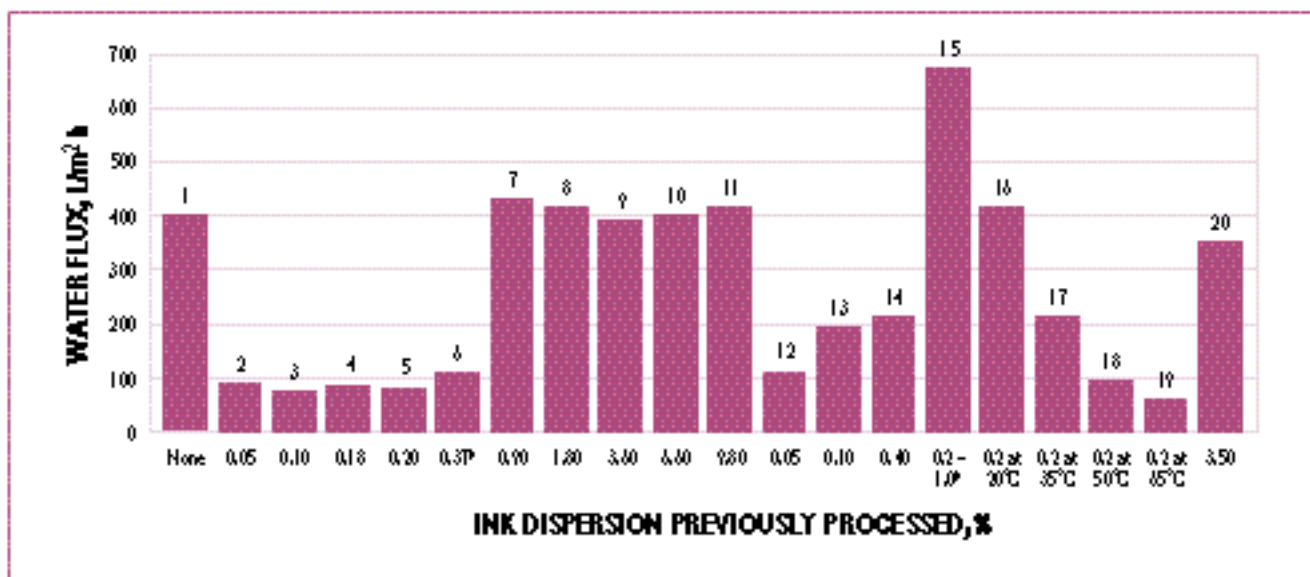
7. Flux vs. ΔP_{tm} at three flow rates, 4.6% ink dispersion

suspensions (electro deposition primer and styrene butadiene latex), including the tendency for the flux vs. $\ln(C_B)$ line to be concave up, which he attributed to variations in shear forces due to viscosity increasing as the feed was concentrated (14). The flux values for dispersions containing less than 0.9% ink do not

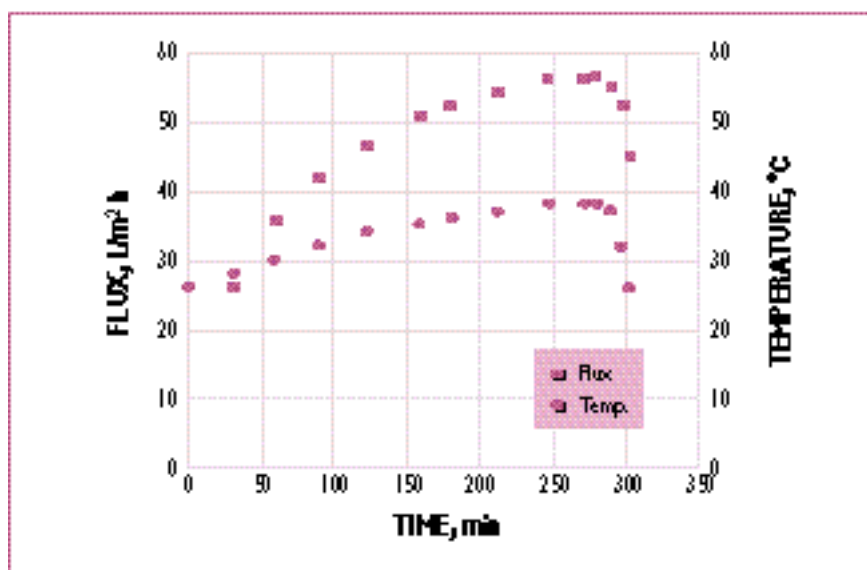
follow the same relationship. This data show that flux was strongly affected by feed concentration when processing high-concentration dispersions, indicating that the gel layer was the limiting resistance to permeate flux. Relative independence of flux on feed concentration was observed when processing low-con-

centration dispersions, indicative of operating under conditions in which the gel layer was not the limiting resistance to permeate flux (14).

Extrapolating the data in Fig. 6 to zero flux predicts that the gel concentration (C_g) was approximately 30% solids. Porter's data for ultrafiltration of colloidal systems pre-



8. Water flux after processing flexographic ink dispersions (* = after extended soaking)



9. Flux and temperature vs. time, 3.5% ink no. 2 at 25 psi

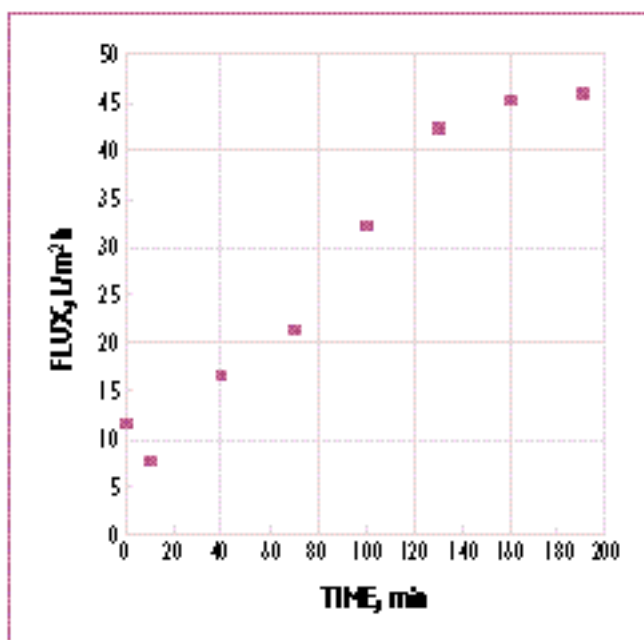
dicted C_g between 60% and 70%; however, the operating conditions during his experiments were not specified (14). Desaulniers and Hausslein attained a maximum solids content of 31% when ultrafiltering an aqueous dispersion of activated carbon particles (median size 11 μ m) in a batch cell using an ultrafiltration membrane with MWCO of 250,000 (18). They also determined that the carbon filter cake on the membrane surface controlled the filtration rate.

The effect of flow rate on permeate flux during cross-flow ultrafiltration is due to the shear forces exerted by flowing fluid at the wall of the membrane, which is instrumental in preventing or controlling the size of a layer of retained pigment on the membrane surface (14, 16, 18). Any pigment layer that forms on the membrane surface will act as a barrier to permeate flow, thus affecting flux negatively. At high flow rates, the formation of a gel

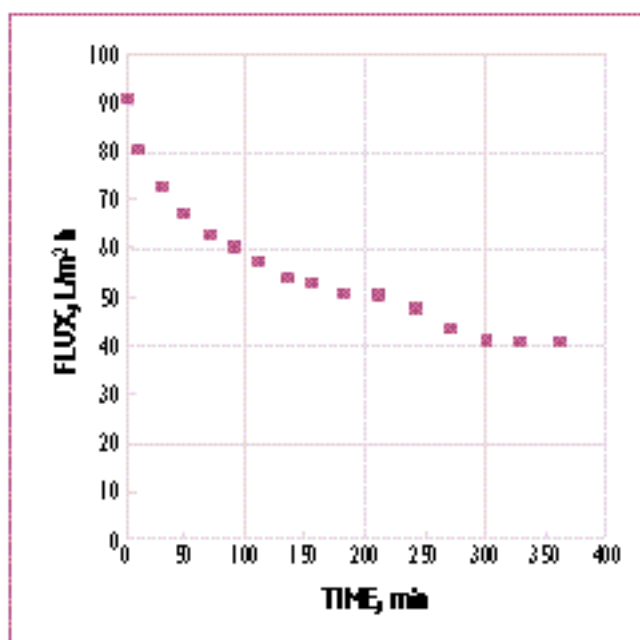
layer will be retarded. This effect was investigated by processing a 4.6% flexographic ink dispersion at three flow rates (0.5, 1.0, and 1.5 gal/min). The experiment was performed in a random manner to preclude any time effects (such as membrane fouling) from entering into the analysis. The desired operating conditions (flow rate and ΔP_{tm}) were tabulated and numbered, and the order in which the data were obtained was determined by a random number generator. The data in Fig. 7 illustrate that better ultrafiltration performance (higher flux) was achieved when operating at high feed flow rates and that mass-transfer controlled ultrafiltration occurred at lower ΔP_{tm} when operating at low flow rates. However, since the data were collected in a random order, complete steady-state operation (including formation of stable pigment layers on the membrane surface) may not have been achieved. Therefore, the effect of flow rate may be greater than that indicated by these results.

Effectiveness of cleaning

The ultrafiltration membrane was cleaned between experiments to ensure that a similar baseline performance was realized prior to process-



10. Flux vs. time, 3.9% ink no. 2 at 25 psi and 20°C



11. Flux vs. time, 0.05% ink no. 1 at 25 psi and 22°C

ing the next ink dispersion and to evaluate the severity of any performance degradation that may have occurred. Membrane performance was characterized by the water flux, which is the flux when processing a 0.01% surfactant solution with pH adjusted to 10, at 25 psi, 20°C, and 1 gal/min feed flow rate. The following is a sequential summary of ultrafiltration experiments and the effectiveness of the cleaning procedure performed after each experiment. **Figure 8** shows the post-cleaning water flux after processing each of the ink dispersions.

When new the ultrafiltration membrane demonstrated a water flux of 400 L/m² h. After processing the first ink dispersion (0.05%, ink no. 1), the water flux after cleaning had decreased to 90 L/m² h. This represents significant membrane fouling, which was not reversible upon membrane cleaning. This trend continued (Fig. 8, bars 2–6), and, after processing the other low-concentration dispersions of ink no. 1 (0.09%, 0.18%, 0.195%, and 0.37%), the final water flux was 104 L/m² h, measured

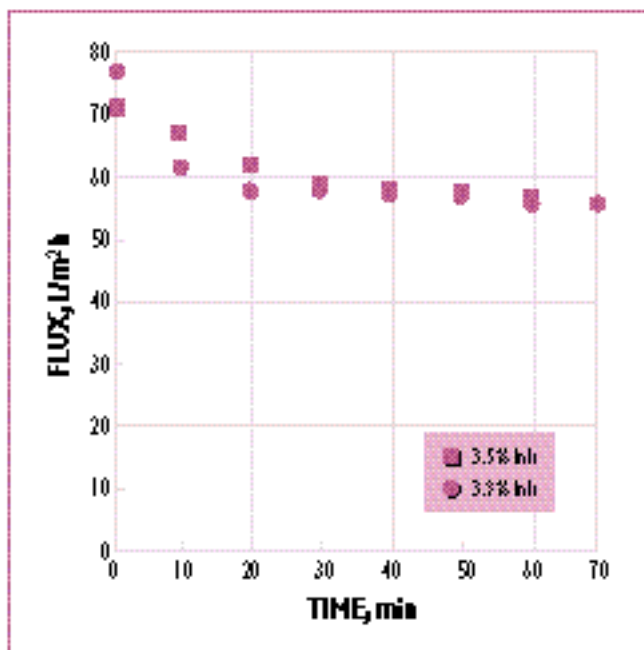
after the membrane had been allowed to soak in a cleaning solution for one month.

Higher-concentration ink dispersions prepared from ink no. 2 were then processed. The water flux after processing a 0.9% ink dispersion and cleaning the membrane was 430 L/m² h, which is higher than that measured with the new membrane. Processing this ink dispersion restored membrane performance better than cleaning with soapy water. Subsequent processing of other dispersions (1.8%, 3.6%, 6.6%, and 9.8%) also resulted in high water flux values after cleaning (Fig. 8, bars 7–11). The final water flux after processing the highest-concentration ink dispersion (9.8%) was 415 L/m² h.

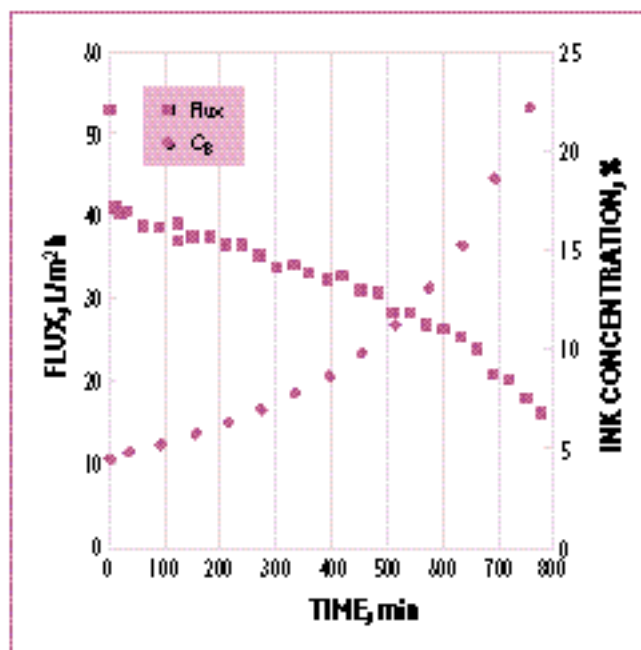
Low-concentration dispersions prepared from ink no. 2 were then processed. The water flux after processing a 0.05% dispersion and cleaning the membrane was 111 L/m² h, indicating that irreversible membrane fouling had again occurred. Two more low-concentration dispersions were processed

(0.1% and 0.4%), and as the ink content of the feed stream increased, the post-cleaning water flux followed, indicating that the membrane was becoming easier to clean (Fig. 8, bars 12–14). The final water flux after processing the 0.4% dispersion was 213 L/m² h.

A dispersion containing between 0.2% and 1.0% ink was processed through the ultrafiltration membrane for approximately 30 minutes. The membrane was then cleaned and allowed to soak in a cleaning solution for approximately two months. The resulting water flux was 672 L/m² h, which was the highest yet measured (Fig. 8, bar 15). At this point, a series of experiments was performed using a 0.2% ink dispersion in which the feed temperature was varied. The results of the temperature study will not be presented; however, the impact on membrane cleaning effectiveness was marked. The experiments were performed at 20°C, 35°C, 50°C, and 65°C. Figure 8 (bars 16–19) shows the water flux values after each of these experiments, which demonstrate that high-



12. Flux vs. time at 25 psi and 20°C



13. Flux and ink concentration vs. time at 25 psi and 20°C

temperature processing was responsible for extensive membrane fouling.

Apparently there was some property of the high-ink-content dispersions that promoted membrane cleaning and restored the water flux, whereas low-concentration dispersions tended to foul the membrane. To investigate this, we processed a 3.5% ink dispersion at 25 psi and 1 gal/min (Fig. 9). Flux increased from 10 L/m² h to 56 L/m² h during the first four hours of the experiment. When the temperature was returned to 26°C, the flux decreased to 45 L/m² h (demonstrating the effect of temperature on flux) (17, 19). After cleaning, the water flux was measured at 350 L/m² h, an increase of 514% from the value prior to this experiment (Fig. 8, bar 20). This is an important finding; it indicates that processing this ink dispersion restored the membrane's performance. A similar experiment was performed at 20°C (Fig. 10) using a 3.9% ink dispersion and an identical ultrafiltration membrane (UF2),

which had been fouled by processing low-concentration ink dispersions at 65°C (the water flux of the membrane was 48 L/m² h). Flux increased from 12 L/m² h to 45 L/m² h after 160 minutes. This is almost identical to the performance observed during the previous experiment. Afterwards the membrane was cleaned, resulting in a water flux of 315 L/m² h, an increase of 556%. These results demonstrate that ultrafiltration of high-concentration ink dispersions has beneficial effects on membrane cleaning.

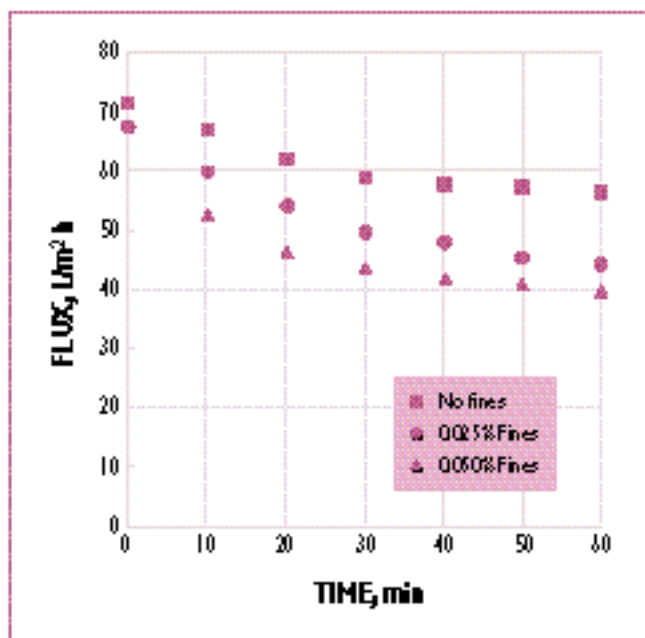
Stable flux during high-concentration ink processing

In the course of a flux vs. ΔP_{tm} experiment, data were collected during at least two complete pressure cycles. Typically, during the first pressure cycle a great degree of hysteresis was observed as the membrane system stabilized. When processing low-concentration ink dispersions, lower flux was observed during the second pressure cycle than during the first pressure cycle, indicating that flux decreased with time. This effect was

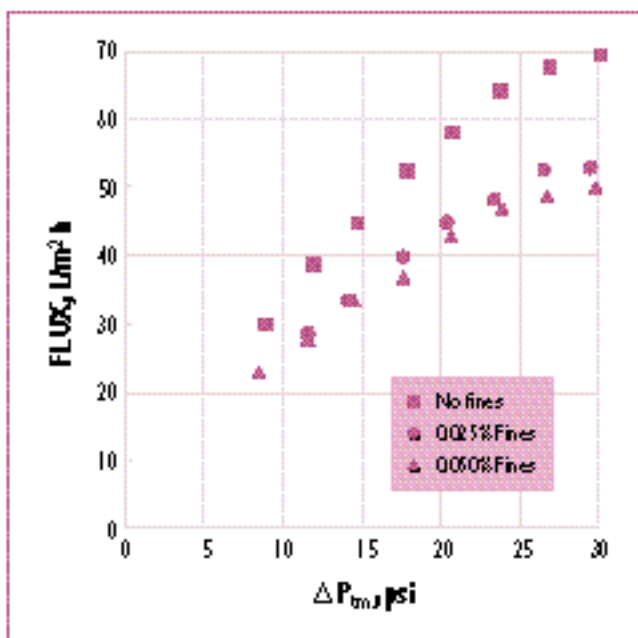
most noticeable for the 0.05% ink dispersion (the lowest concentration processed).

The flux vs. ΔP_{tm} data from processing high-concentration ink dispersions show different trends. Higher flux was attained during the second pressure cycle than during the first pressure cycle for each dispersion that contained 0.9% ink or more. This effect was less noticeable for the 6.6% and 9.8% ink dispersions, but was quite pronounced for the 0.9% and 1.8% dispersions. The 0.9% dispersion was processed through three pressure cycles, with maximum fluxes observed of 72 L/m² h, 110 L/m² h, and 130 L/m² h during the first, second, and third pressure cycles, respectively. This indicates that flux increased with time.

Figure 11 shows a plot of flux vs. time for ultrafiltration of a 0.05% dispersion of ink no. 1 at constant pressure (25 psi) and temperature (22°C), with the permeate recycled back to the feed tank so that the ink concentration remained constant.



14. Flux vs. time, 3.5% ink no. 2 with and without cellulose fines (25 psi, 20°C)



15. Flux vs. ΔP_{tm} , 3.5% ink no. 2 with and without cellulose fines (25 psi, 20°C)

The initial flux was 91 L/m² h and decreased to 41 L/m² h over a five-hour period. Over the next 60 minutes the flux changed only slightly. During ultrafiltration of a 3.5% ink dispersion, the flux decreased from 71 L/m² h to 58 L/m² h in the first 30 minutes, and then changed very little during the next 30 minutes with a final flux of 56 L/m² h after one hour of operation (Fig. 12). When a 3.9% ink dispersion was processed, the flux decreased from 78 L/m² h to 58 L/m² h after only 20 minutes of operation (Fig. 12). Continued processing resulted in the flux decreasing to 56 L/m² h after 70 minutes of operation. These data demonstrate that stable flux can be achieved when processing high-concentration ink dispersions. Not only is flux more stable with time, but higher flux levels were attained when processing the high-ink-content dispersions than when processing the low-ink-content dispersions. After one hour of ultrafiltering a 0.05% ink dispersion, the flux had decreased to 65 L/m² h and was still decreasing, as

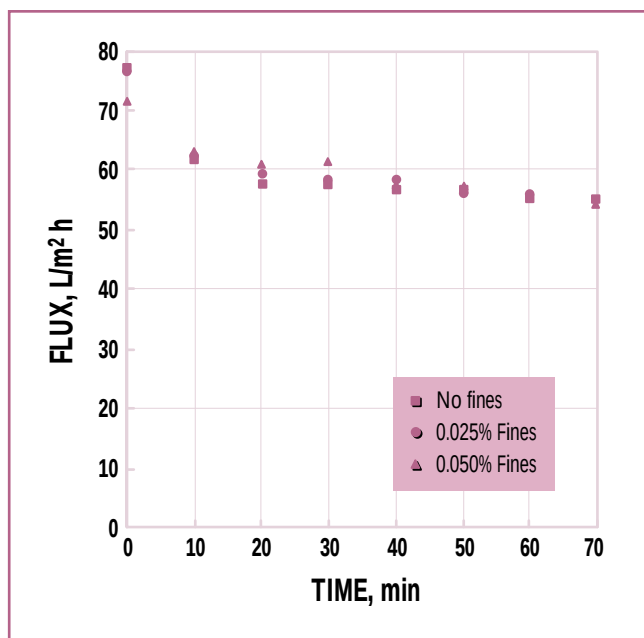
shown in Fig. 11. The final flux was 41 L/m² h. Ultrafiltration of a 3.5% dispersion with the same membrane under identical conditions for one hour resulted in a stable flux value of 56 L/m² h, over 36% higher than that achieved when processing the 0.05% dispersion.

Effective clarification of flexographic ink dispersions entails concentrating the pigment to as high a level as possible as permeate (water and other dissolved species) is removed, while maintaining high flux rates. To evaluate the capabilities of ultrafiltration to achieve this goal, an experiment was performed in which permeate was removed from the system as it was produced, causing the ink concentration of the feed to increase as ultrafiltration progressed (Fig. 13). The initial ink concentration was 4.4%, and increased to 22.2% after 755 minutes of operation. After an initial rapid drop, flux decreased gradually as the ink concentration increased. At an ink concentration of 22.2% the flux had decreased to 18 L/m² h.

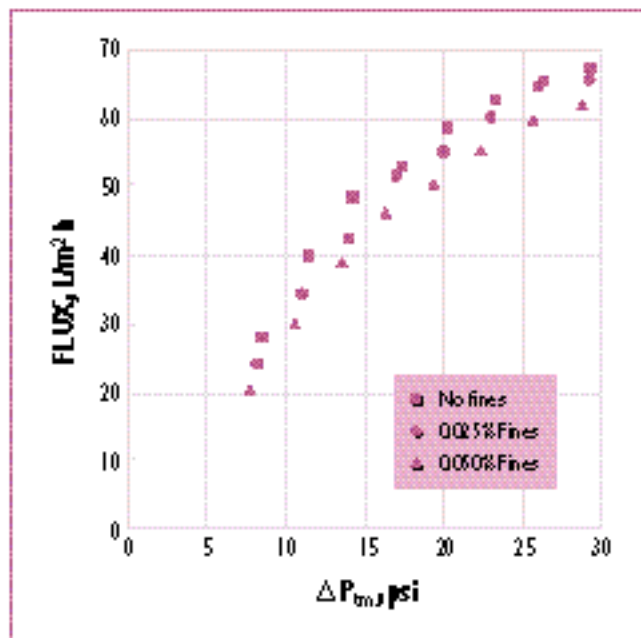
The stable high flux values observed when processing high-concentration ink dispersions could be due to a filtering action of the gel layer of pigment formed during mass-transfer controlled ultrafiltration. The carbon black pigment particles in flexographic inks are very small, with 90% of the particles less than 5 μm in size and a considerable fraction below 0.2 μm (20). The smallest of these particles could enter or partially block some of the pores in the ultrafiltration membrane, reducing flux irreversibly. However, the gel layer could act as a filter aid, preventing even the smallest pigment particles from reaching the membrane surface. Closely packed cakes of micron or submicron particles have high hydraulic permeabilities (21), facilitating high flux levels while promoting long-term stability of flux by preventing membrane fouling.

Addition of cellulose fines

To evaluate the potential effects of cellulose fines on ultrafiltration of flexographic ink dispersions, a series



16. Flux vs. time, 3.9% ink no. 2 with and without cellulose fines (25 psi, 20°C)



17. Flux vs. ΔP_{tm} , 3.9% ink no. 2 with and without cellulose fines (25 psi, 20°C)

of experiments was performed in which fines were added to the ink dispersion. Constant-pressure ultrafiltration (25 psi at 1 gal/min) for one hour was followed by a pressure cycle in which the flux vs. ΔP_{tm} relationship was investigated. Cellulose fines were then added and the experiment repeated. The membrane was cleaned between each step to evaluate the effect of fines on cleaning effectiveness.

The data for processing a 3.5% ink dispersion with and without fines are presented in Figs. 14 and 15. The results indicate that inclusion of low amounts of cellulose fines decreased the ultrafiltration performance (flux levels); however, the effectiveness of membrane cleaning did not appear to be significantly affected. The after-cleaning water fluxes after processing these feeds were 290 L/m² h (no fines), 302 L/m² h (0.025% fines), and 306 L/m² h (0.05% fines).

Results for the ultrafiltration of a 3.9% ink dispersion with and without fines are shown in Figs. 16 and

17. These results indicate that the presence of low amounts of cellulose fines did not significantly affect ultrafiltration performance, in contrast to the previous results. The presence of 0.025% fines had virtually no effect on ultrafiltration performance, and the presence of 0.05% fines had only a minimal effect. The effectiveness of membrane cleaning was not affected by fines, in agreement with the previous results. The after-cleaning water fluxes after processing these dispersions were 276 L/m² h (no fines), 262 L/m² h (0.025% fines), and 285 L/m² h (0.05% fines).

CONCLUSIONS

During ultrafiltration of flexographic ink dispersions the permeate was free of ink pigments, demonstrating the capability of ultrafiltration to completely remove flexographic residues from wash effluent.

Flux was directly proportional to ΔP_{tm} during ultrafiltration of low concentrations of flexographic ink (less than 0.4%) and high ink con-

centrations (greater than 0.9%) at low operating pressure. This is indicative of operating under conditions in which the membrane, and not a gel layer of pigment, presents the limiting resistance to permeate flux.

At ink concentrations of 0.9% and above, flux decreased exponentially with increasing concentration. Flux was relatively independent of ink concentration at lower concentrations.

Ultrafiltration of low-concentration flexographic ink dispersions resulted in irreversible membrane fouling. Performance could not be restored by cleaning after processing these dispersions. The cleaning procedures appeared to be quite effective after processing high-concentration flexographic ink dispersions. In fact, processing high-concentration ink dispersions had beneficial effects on performance and restored high flux levels to ultrafiltration membranes that had previously been fouled by processing low-concentration dispersions.

KEYWORDS

Aniline printing, cleaning, deinking, effluent treatment, filtration, flexography, flow, fouling, ink, letter press printing, newsprint, printing, printing ink, printing papers, separation, technology, ultrafiltration.

Flux was observed to decrease with time when processing low-concentration flexographic ink dispersions, indicative of membrane fouling. However, when ultrafiltering high-concentration dispersions flux was stable with time. In some cases,

higher flux was obtained by increasing the ink content of the feed stream. This indicates that the gel layer formed during mass-transfer controlled ultrafiltration prevented small pigment particles from fouling the membrane.

The addition of small amounts of cellulose fines to flexographic ink dispersions did not drastically affect ultrafiltration performance. Cellulose fines had no effect on membrane fouling, as demonstrated by the effectiveness of the cleaning procedure after processing ink dispersions containing fines. **TJ**

Upton is a graduate research assistant and

Krishnagopalan is an associate professor in the Department of Chemical Engineering, Auburn University, Auburn, AL 36849.

Abubakr is a project leader at the USDA Forest Products Laboratory, One Gifford Pinchot Dr., Madison, WI 53705-2398.

The authors wish to express their appreciation for financial support from the USDA Forest Products Laboratory, Madison, WI, Koch Membrane Systems, Inc., and the Auburn University Pulp and Paper Research and Education Center.

Received for review Jan. 31, 1995.

Accepted Feb. 8, 1996.

Presented at the TAPPI 1995 Environmental Conference.

LITERATURE CITED

1. Ferguson, L. D., *TAPPI 1993 Deinking Short Course Notes*, TAPPI PRESS, Atlanta.
2. Galland, G. and Vernac, Y., *Pulp Paper Can.* 94(6): 71(1993).
3. Putz, H. J., Schaffrath, H. J., and Götsching, L., *Pulp Paper Can.* 94(7): T193(1993).
4. Seifert, P., *TAPPI 1992 Pulping Conference Proceedings*, TAPPI PRESS, Atlanta, p. 917.
5. Pan, R., Paulsen, F. G., Johnson, D. A., Bousfield, D.W., et al., *TAPPI 1993 Pulping Conference Proceedings*, TAPPI PRESS, Atlanta, p. 1155.
6. Ferguson, L. D., *TAPPI 1993 Deinking Short Course Notes*, TAPPI PRESS, Atlanta.
7. Ellis, M. E., Hou, M., and Seenivasan, N., *TAPPI 1993 Pulping Conference Proceedings*, TAPPI PRESS, Atlanta, p. 767.
8. Forester, W. K., *TAPPI 1991 Pulping Conference Proceedings*, TAPPI PRESS, Atlanta, p. 234.
9. Horacek, R. G., *TAPPI 1993 Deinking Short Course Notes*, TAPPI PRESS, Atlanta.
10. Wallström, E., *Adv. in Printing Sci. and Tech.* 19: 199(1988).
11. Skelton, R., *Converter* 22(4): 14(1985).
12. Upton, B. H., Krishnagopalan, G. A., and Abubakr, S., *TAPPI 1994 Recycling Symposium Notes*, TAPPI PRESS, Atlanta, p. 17.
13. Cheryan, M., *Ultrafiltration Handbook*, Technomic Publishing, Lancaster, PA, 1986, p. 76.
14. Porter, M. C., *Ind. Eng. Chem. Prod. Res. Develop.* 11(3): 234(1972).
15. Trettin, D. R. and Doshi, M. R., *ACS Symposium Series* 154(2): 373(1981).
16. Davis, R. H., *Separation and Purification Methods* 21(2): 75(1992).
17. Forbes, F., *The Chemical Engineer* 1: 29(1972).
18. Desaulniers, C. W. and Hausslein, R. W., *FWQA Report No. ORD-17020D BA03/70*, U.S. Dept. of the Interior, U.S. Government Printing Office, Washington, DC, March 1970.
19. Jönsson, A. S. and Wimmerstedt, R., *Desalination* 53: 181(1985).
20. Liphard, M., Schreck, B., and Hornfeck, K., *TAPPI 1990 Pulping Conference Proceedings*, TAPPI PRESS, Atlanta, p. 965.
21. Blatt, W. F., David, A., Michaels, A. S., et al., *Membrane Science and Technology*, Plenum Press, New York, pp. 47-97(1970).