

Operational issues in high-speed curtain coating of paper, Part 1: The principles of curtain coating

NICK TRIANTAFILLOPOULOS, JOHAN GRÖN, IIRO LUOSTARINEN, AND PETRI PALOVIITA

ABSTRACT: Curtain coating is emerging as a new coating process for specialty and printing paper grades, and for paperboard. The method features a liquid sheet that falls freely before impinging onto the moving paper web to be coated. High impinging velocity allows coating at relatively high web speeds. This non-contact coating method does not put mechanical stresses onto the substrate to be coated, thus minimizing web breaks and providing good contour coating coverage, which offers opportunities for improved productivity and reduced coat weight. An operational stability diagram governs the process, which needs to be determined *a priori* for optimum operation under specific conditions. In spite of its advantages, the curtain coating process is susceptible to operational defects, such as irregular heel formation, air-entrainment, and curtain instabilities. These problems can be avoided by formulating coatings specifically for curtain applications and optimizing curtain operating parameters. Successful implementation of curtain coating for highly pigmented aqueous coatings at high speeds requires removal of the thin air layer entering the curtain impingement zone on the paper surface to avoid air intrusion, which disrupts coating transfer. We must also suppress the formation of small air bubbles entrained into the coating (i.e., de-aeration).

Application: This paper reviews the basic principles of curtain coating and discusses origins of coating defects. It provides operational insights pertaining to high-speed application of highly concentrated aqueous paper coatings.

Curtain coating is a common preme-
tering method used for precision
coating. It features a liquid sheet that falls
freely before impinging onto the sub-
strate to be coated. It is ideal for applying
thin films onto irregular surfaces at high
speeds [1]. Thin coatings result from the
large distance between the die opening
and substrate, and the relatively high
velocity of the impinging jet, compared to
the vertical velocity component of the
moving web. High impinging velocities
allow coating at high web speeds.

In spite of its advantages, curtain coat-
ing is susceptible to limiting operational
conditions. There is a lower limit in the
flow rate; below this limit the falling sheet
abruptly breaks up. Another issue is relat-
ed to sensitivity of the unsupported free
fluid sheet to disturbances that eventual-
ly cause coating irregularities. Finally,
process speed limitations arise from air
entrainment at the contact of impinge-
ment of the curtain with the substrate.

Several types of curtain coating appli-
cators have been used since the 1960s to
coat continuous webs. Applications
included coating aluminum foil and cor-
rugating board at speeds as high as 480
m/min [2, 3]. Modern designs are used for
single and multilayer coatings in

precision film formation, such as the one
required for making photographic films.
Although various feeding die designs have
been patented, we've concentrated on
the slot-fed design (Fig. 1), similar to the
one patented by Hughes [4]. Additionally,
we focus on single falling-film flows relat-
ed to aqueous pigmented coatings.

The principles and operability of cur-
tain coating have been studied extensive-
ly with theoretical analyses, experiments,
and finite-element modeling. The process
can be separated into three regions: the
sheet forming zone, the curtain flow
sheet, and the impingement region, as
shown in Fig. 2 [5]. The slot-fed design is
characterized by two static contact lines
in the sheet-forming region, where the jet
exits the die.

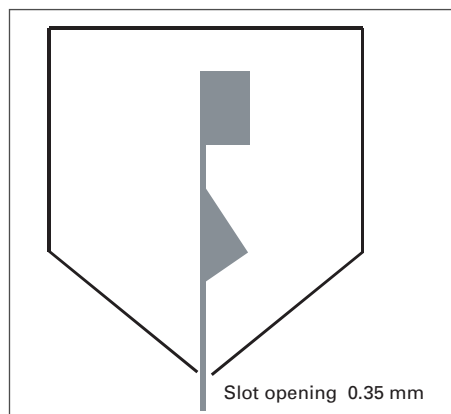
PHYSICS OF CURTAIN COATERS

Sheet forming

Analysis of the flow from slot-fed curtains
has been well documented by Kistler [5].
The freely falling film attains extensional
flow within a short distance (about 100-
300 mm) from the slot opening. Gravity,
inertia, and viscous and capillary forces
control the spread of the film as it moves
toward the substrate. Forces at the static

contact lines lead to an uneven distribu-
tion of stress near the slot opening, caus-
ing the film to sometimes deflect toward
the underside of the opening. Conse-
quently, the contact line migrates
away from the opening, causing a "teapot
effect."

Along with curtain deflection, two
other mechanisms correlate to teapot
effect [5, 6]. The first is the difference
between the advancing and receding
contact angles arising from incongruities
and surface roughness of the slot-die
material. The second is traditional hydro-
dynamic instabilities of the free surface
flow, which lead to multiple states of
flow under the same flow parameters.
Curtain deflection originates from pure
hydrodynamic effects, not from dynamic
wetting or spreading phenomena [6].
The dimensionless Reynolds number, Re ,
expressed as the flow rate per unit
width, is the controlling parameter. When
the flow rate, and therefore the Reynolds
number, increases, the contact line
migrates further away from the slot open-
ing. However, there is a critical flow rate
for maximum deflection, after which the
film starts moving towards the slot
opening. Although this phenomenon is
hydrodynamic in nature, finite-element-



1. Slot-fed type curtain die for paper coating.

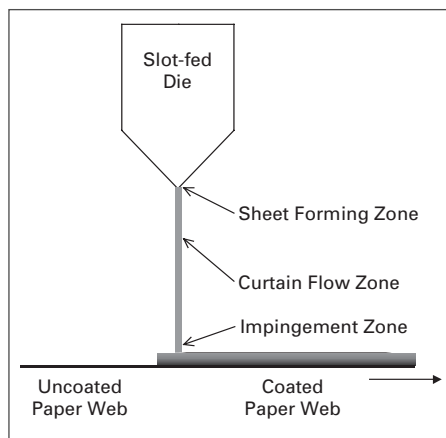
method results indicate that the position of the contact angle is less sensitive to flow rate when the contact angle increases.

The teapot effect is generally undesirable because it can lead to coating defects. These include trapping material beneath the lip, and significant deviation of the curtain from the vertical position. The first can lead to dried-out deposits in the dead zones of flow, which can deform the slot opening. The second problem is associated with formation of cross-directional streaks. The teapot phenomenon is more common with slide coaters, not curtain slot coaters where the slot lip designs have been optimized.

THE CURTAIN

The key variable of the flow in the curtain zone is the final velocity, V , with which the fluid impinges onto the web. This velocity always points downwards in the direction of gravity and critically defines the operational window of the process. Under certain conditions, capillary forces at the impingement region can “pull” the curtain in the direction of the web movement. Pulled films can break. This is a phenomenon observed when the flow rate is relatively low or the curtain height is small. It is manifested by the requirement that, for a stable curtain, velocity V needs to be larger than the propagation velocity of the free edge of a curtain, the latter being proportional to surface tension and inversely proportional to the local thickness of a curtain.

Long curtains, which are preferred for delaying air entrainment and applying thinner films, are more difficult to form



2. Flow zones in the curtain coater, e.g., the sheet forming zone, the curtain flow zone, and the impingement zone [5].

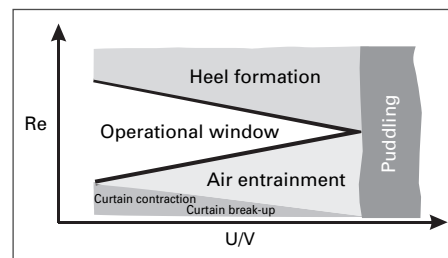
and maintain uniformly in practice. Greiller [7] demonstrated that there is an optimum range of viscosities and surface tensions for maintaining a stable curtain. Raising the viscosity of pure fluids stabilizes the curtain by damping hydrodynamic disturbances. At the same time, it accelerates boundary layer growth when the film contacts the web. This, in turn, causes curtain disruption. Surfactants reduce surface tension and increase surface elasticity, reducing the propagation velocity. Their presence at the edge of a curtain can prevent contraction of the curtain, by increasing wettability of the edge guide, or induce contraction due to the Marangoni effect, the localized surface tension gradients. On the other hand, low curtain velocities are associated with curtain instabilities resulting from viscous boundary drag along the curtain edge guides [8].

The stability of a curtain depends on the ratio of inertial to surface tension forces. This is known as the dimensionless Weber number (We):

$$We = \frac{\rho Q V}{\sigma} \quad (1)$$

where ρ and σ are respectively the fluid density and surface tension, and Q is the volumetric flow rate per unit width. A stable curtain requires that inertia forces are greater than surface tension forces, or $We > 2$, a criterion expressed as:

$$We = \frac{\rho Q V}{\sigma} = \frac{\rho \sqrt{2gx} H_{wet} V}{\sigma} \geq 2 \quad (2)$$



3. The operational window for curtain coating described by the Reynolds number (Re) as a function of the dimensionless speed ratio (U/V).

hence, H_{wet} is the wet film thickness deposited on the web and x is the length of the curtain measured from the die lip. The following criteria aid curtain stability: (a) thick curtains, (b) fast moving curtains, (c) high volumetric flow rate per unit width, and (d) low surface tension [8]. Low surface tension allows for lower coating weight at constant web speed, or low web speed to achieve a targeted coat weight. In other words, reducing the surface tension widens the operational window of the process. Although viscosity does not appear in Eq. 2, it proportionally influences the length (“transition zone”) within which viscous forces inhibit curtain velocity. Curtains of high viscosity can be stable if $We < 2$, when the curtain is shorter than the transition zone length, which increases with high viscosities [8].

Beyond theory, Schweizer [8] suggests practical guidelines for stable curtains: (a) flow rates above a certain minimum, and (b) surface tension below a maximum. For aqueous fluids, the minimum flow rate is about 1.0 cm²/s per centimeter width, while the maximum surface tension is 40 mN/m. For any given wet film thickness, and correspondingly dry coverage, A_{dry} in g/m², there exists a minimum web speed:

$$V > \frac{1000 \rho c Q_{min}}{A_{dry}} \quad (3)$$

hence, c is the solids concentration. For example, for a solids concentration of 50%, a coating weight of 5 g/m² requires a minimum web speed of 600 m/min. A low surface tension is difficult to satisfy with aqueous fluids because the surface tension of water is 70 mN/m. Surface active agents (surfactants) must be added. Their effectiveness is primarily

controlled by their diffusivity from the bulk to the free surface of the curtain fluid—a process that is time dependent. The following are some of the many variables that influence the effectiveness of stabilizing a curtain through addition of surfactants:

- The chemical structure, chain length and concentration of surfactant molecules
- The viscosity of the curtain fluid
- The local velocities in the curtain flow field
- The age of the curtain fluid
- The rate at which fresh curtain surface is generated [8].

Low surface tension requires high surfactant concentration or long surface aging. “Dynamic surface tension”—the time-dependent surface tension of the curtain fluid that takes into consideration aging—has practical use. At long surface age, the dynamic surface tension approaches the equilibrium values of static surface tension.

Edge effects also influence curtain stability. Edge effects can cause local thinning of the curtain near the edge guides and break up the curtain [1] (see Schweizer [8], for more detailed information on edge effects).

The unsupported curtain is also susceptible to small disturbances arising from pressure differentials [9]. These disturbances are typically periodic, creating a swinging motion of the curtain, much like a moving pendulum. The result is barring in the coated film. In addition, ambient air flow currents can periodically disturb the curtain.

THE IMPINGEMENT REGION

The prevailing physics at the region where the curtain impinges onto the moving web also determines the process operational window. Critical parameters are the Reynolds number (**Re**), the ratio of the inertial force (acceleration) to the net viscous force:

$$Re = \rho Q / \mu \quad (4)$$

hence, μ is the fluid viscosity; the ratio of the web speed U to the impingement velocity, V ; and the Weber number (Eq. 1) [5]. Additionally, another dimensionless number that influences the impingement flow is the Stokes number (**St**), the

ratio of gravity forces (except hydrostatic forces) to the net viscous force:

$$St = \rho g Q^2 / \mu U^3 \quad (5)$$

In high-speed curtain coating, inertia, viscosity, and particularly surface tension forces play a key role. Formation of a heel in the impingement zone (Fig. 2), that moves the dynamic contact angle upstream, is promoted by high **Re**, high flow rates, or low speed ratios. It is retarded at small **Re** and large values of the speed ratio. Downstream from the impingement region, the flow evolves into a parallel, fully-developed flow, which is driven by the high shear stresses exerted by the moving web. The existence and evolution of the heel defines the operational window of the process. When the heel grows, it encompasses recirculating vortices, which can entrain air bubbles that cause coating defects, such as streaks. Heels are also sensitive to periodic instabilities that result in cross-directional film nonuniformity. Finally, formation of a heel is closely associated with air-entrainment, which creates visible skip coating.

While the unsupported curtain is susceptible to disturbances, the fluid in the impingement zone is more tolerant to disturbances than are coating beads in other pre-metering methods [10]. Governing parameters are the Reynolds number (**Re**), the speed ratio (**U/V**), and the capillary number (**Ca**):

$$Ca = \mu V / \sigma \quad (6)$$

Kistler [5] demonstrated that, for the limiting case where **Ca** approaches infinity, the coatability window of the impinging jet can be described in graphs of **Re** and the velocity ratio (**U/V**). Critical phenomena include the following:

- Curtain breakup at low flow rates
- Pulled phenomenon at low flow rates and slow coating speeds
- Air entrainment at high speeds and low flow rates
- Heel formation at high flow rates and slow speeds
- Air entrainment with heel formation at high flow rates and fast speeds.

Because of practical interest for paper coating applications are relatively high speeds, air entrainment at the

impingement zone becomes a major consideration.

Generally, the high pressures of the impinging jet can effectively displace air intrusion from the air film that travels with the moving web. The position of the contact (wetting) line depends on both macroscopic and hydrodynamic effects (the inertia of the impinging jet and the momentum transfer that accelerates the coating film in contact with the web at a given volumetric flow rate). Small heels form at relatively low **U/V** and low **Re** numbers, and with large surface tension, which decreases the length of the boundary layer. Formation of a heel as flow rate increases contributes to air entrainment. The mechanism involves eddies, which are encapsulated inside the heel, that trap air bubbles, but can also retain agglomerated particles. In addition, heel formation at high speeds leads to an uneven contact line, which can then introduce cross-directional nonuniformities running in the machine line direction.

Brown [11] and Hughes [4] reported that curtain coating could operate at speeds of 360 m/min and 600 m/min without air entrainment. Nevertheless, air intrusion is still the key factor in high-speed curtain coating. There is always a coating speed limit above which air bubbles start entering the coating film from V-shaped air pockets formed at the moving (wetting) contact line. As a result, craters appear in the formed film. In the extreme case, skip coating can occur [12]. A more detailed description of the mechanisms of air entrainment is included in Miyamoto and Scriven [13]. The operational window to avoid defects arising from air entrainment is defined by the Reynolds number and speed ratio, **U/V**. Shear thinning fluids facilitate rapid flow development at the wetting line, thus delaying onset of air entrainment [5]. Computer simulation of the impingement zone indicates that increasing the shear-thinning behavior of fluids shifts the onset of cavitation to high operational speeds [14]. Cavitation, manifested by the contact line at the heel pulled by the moving web and deflecting the curtain, causes curtain film rupture.

The coating process at high flow rates is bound by a maximum coating speed to avoid massive air entrainment at the heel [1]. Long heels tend to reduce the

positive effects of hydrodynamics on wetting, causing air layers to be drawn into the boundary layer and creating slip. The surface energy of the substrate, and its roughness, determine the maximum coating speed. In practice, curtain surface and wettability are controlled with surfactants added to the coating.

Heel formation and curtain stability determine the maximum and minimum film thicknesses achieved with a curtain coater [5, 15]. The maximum thickness is limited by the flow down of the curtain, which is affected by viscous drag and gravity. The minimum thickness is controlled by the requirement for a certain flow rate to form a stable falling film. Interestingly, there is no direct influence of the coating gap—the distance of the die lip from the substrate. The indirect effect is solely related to the impinging curtain velocity.

THE OPERATIONAL STABILITY DIAGRAM

Determining the operational window is an important step toward optimum use of the curtain coating method. In its dimensionless form, the window looks like Fig. 3. The key lies in selecting flow parameters incorporated in the Reynolds number, Re , and the speed ratio, U/V . These parameters allow us to closely control the position of the dynamic contact angle at the impingement zone and to achieve the desirable coat weight. At a very low Re and U/V , the curtain is pulled and starts to contract at the edges. The pulled film will finally break up as U/V continually increases. Low Re numbers allow air to be entrained between the meniscus and the paper surface; the curtain breaks up. Very high Re numbers result in heel formation. The window gets narrower at high-speed ratios; hence the flow rate becomes more critical. Beyond a certain speed ratio, there will be "puddling" appearing as CD-patterns on the coated surface. The effective operational window strongly depends on coating viscosity—and therefore coating solids—and relative speeds (web vs. curtain). In aqueous paper coatings, surface tension, although important, can only be changed slightly by the choice of formulation components with surface-active agents (i.e., surfactants, dispersants, latexes). Viscosity, on the other hand, can be

readily changed by orders of magnitude by simply increasing or decreasing coating solids.

CURTAIN COATING FOR PIGMENTED PAPER COATINGS

In recent years, several pilot coater trials have evaluated the curtain coating process for highly pigmented paper coatings for commodity paper grades [14, 16-18] and to share practical experience from application in thermal paper manufacturing [19]. Focus has been on determining the limits of the process at high operational speeds (i.e., above 1000 m/min) and on optimizing coating rheology and paper surface quality.

By removing the air layer at speeds exceeding 400 m/min, it has been possible to coat at LWC web speeds from 1500 to 2000 m/min [16]. Curtain coating gives possibilities to apply low coat weights (5.8 g/m²) in LWC with high coverage (85%), even at low coating solids (54%)—kept low to help removal of air bubbles. At a constant coat weight of 5-6 g/m², there was about 40% advantage in coating coverage using the curtain coater instead of a metered size press.

Pilot coater trials for offset printing paper and paperboard were conducted in Germany by the "High Speed/Solids Pigment Curtain Coating" consortium [17]. Coating requirements were identified as: high solids—low viscosity coatings and surface tension, high coating elasticity and "stretchability," and low air bubble content. Successful applications included all-carbonate, carbonate/kaolin, carbonate/kaolin/TiO₂ pigments in all-synthetic thickener coatings at about 50%-55% solids. Applications included LWC and woodfree paper coating at 1000 m/min, as well as paperboard coating.

Voss and Tadjbach [18] demonstrated that, by increasing the stretchability of a coating, an improved LWC quality could be achieved with curtain coating. Pilot coating was possible for a 42 g/m² LWC base paper at machine speeds from 1200 to 1600 m/min for a coat weight target of 12 g/m² with 61% solids coatings using different thickeners. An increase in extensional viscosity led to a reduction in coating surface defects under the selected pilot coater conditions. Focusing on coating rheology, the

authors discussed the *Trouton ratio*, which correlates shear and extensional viscosities. For Newtonian fluids, the ratio is 3. For non-Newtonian paper coatings, values of 3-6 for coatings with limited efficiency thickeners were found. The ratio was about 10 for coatings that corresponded to defect-free curtain coater runnability. A selected polyacrylate coating thickener displayed improved coating image, especially at high concentrations. However, an extensional viscosity limit would exist, corresponding to a certain coater speed. If a paper coating exceeds this limit, tension on the curtain and the extensional forces could become too high, causing curtain break up or splitting and interfering with curtain impingement.

CONCLUDING REMARKS

Non-contact coating methods, such as curtain coating, open the possibility for improving coating coverage and reducing, if not eliminating, web breaks at the coater. The slot-die curtain coater could be useful for coating light paper grades and paperboard. There are, however, certain quality restrictions limiting the method for paper coating, including control of the boundary air layer and air bubbles in the coating. Part II of this study will provide practical details of our experience from pilot coater trials. Resolution of mechanical design challenges to manufacture precise, wide die slots and to process highly pigmented coatings at high speeds, with subsequent air bubbles removal, will dictate the effectiveness of curtain coating for manufacturing commodity grades of paper and paperboard. Foremost, however, is the need to define an attractive value proposition for using a new process with a steep learning curve. **TJ**

LITERATURE CITED

1. Miyamoto, K., and Katagari, Y. in *Liquid Film Coating* (S. Kistler and P. Schweizer, Eds.), Chapter 11c, Chapman & Hall, London, 1997, pp. 463-494.
2. Poirier, C.C., *TAPPI J.*, 49(10): 66A(1966).
3. Booth, G.L., *Coating Equipment and Processes*, Lockwood Publishing, New York, 1970.
4. Hughes, D.J., "Method for simultaneously applying a plurality of

- coated layers forming a stable multilayer free falling vertical curtain," U.S. pat. 3,508,947 (1970).
5. Kistler, S. F., "The fluid mechanics of curtain coating and related viscous surface flows with contact lines," Ph.D. thesis, University of Minnesota, Minneapolis, 1983.
 6. Kistler, S.F. and Scriven, S.E., *J. Fluid Mech.*, 263: 19(1994).
 7. Greiler, J.F., "Method for making photographic paper," U.S. pat. 3,867,901 (1972).
 8. Schweizer, P., *Paper Techn.*, 45(3): 28(2004).
 9. Finnicum, D.S., Weistein, S.J., and Ruschak K.J., The effect of applied pressure on the shape of a two-dimensional liquid curtain falling under the influence of gravity, *J. Fluid Mech.*, 255: 647-655(1993).
 10. Scriven, S., *Coating flows and coating rheology*, instructional seminar notes, University of Minnesota, Minneapolis, June 2001.
 11. Brown, D.R., *J. Fluid Mech.*, 10: 297(1961).
 12. Miyamoto, K., "On the nature of entrained air bubbles in coating," 1986 AIChE [American Institute of Chemical Engineers] *Conference Proceedings*, New Orleans, Louisiana.
 13. Miyamoto, K., and Scriven, L.E., "Breakdown of air film entrained by liquid coated on web," 1982 AIChE *Conference Proceedings*, Los Angeles, CA.
 14. Alleborn, N., Rasziller, H., and Sünderhauf, H., "High-speed curtain coating of paper," *Proceedings from the 2001 20th PTS Coating Symposium*, (R. Sangl and H. Runge, Eds.), PTS, Munich, Germany. Presentation 32, p.1.
 15. Miyamoto, K., "On the difference of three die coating methods," *Proceedings of the 2000 10th International Coating Science and Technology Symposium*, Scottsdale, AZ. pp. 105-107.
 16. Triantafillopoulos, N., J. Grön, J., I. Luostarinen, I., P. Paloviita, P., "Operational issues in high-speed curtain coating of paper," 2001 TAPPI *Coating Conference Proceedings*, TAPPI PRESS, Atlanta, Georgia, USA, p. 251.
 17. Meck, D., Kogler, W., Becker, I., Holtmann, B., Stuffer, P., "Non-impact coating in curtain coating," *Proceedings of the 2001 20th PTS Coating Symposium*, (R. Sangl and H. Runge, Eds.), PTS, Munich, Germany. Presentation 34, p.1.
 18. Voss, M., and Tadjbach, S., "Optimizing curtain-coating colours for graphic papers," *Proceedings of the 2003 21th PTS Coating Symposium*, (R. Sangl and H. Runge, Eds.), PTS, Munich, Germany. Presentation 30, p. 1.
 19. Stegner, D., and Trefz, M., "Practical experience gathered with the curtain coater at Kehl mill," *Proceedings of the 2003 21th PTS Coating Symposium*, (R. Sangl and H. Runge, Eds.), PTS, Munich, Germany. Presentation 31, p. 1.

Received: November 24, 2001

Revised: February 26, 2004

Accepted: August 8, 2004

This paper is also published on TAPPI's web site <www.tappi.org> and summarized in the November *Solutions! for People, Processes and Paper* magazine (Vol. 87 No. 11).

INSIGHTS FROM THE AUTHORS

Looking with vision toward new paper coating processes to improve productivity and product quality, we studied the possibility of using curtain coating—a process used for coating specialty papers—in mass-produced publication grades, seeking to define a new value proposition. Extensive work has been done in curtain coating specialty grades of paper and paperboard, but little has been published on the potential value of such a process in mass-produced paper grades and the operational challenges of making that application work.

One of the biggest challenges we faced during the pilot coater testing turned out to be fine air bubble removal from high-solids coating colors. Our efforts to meet this challenge actually led to the development of a whole new degassing device.

A particularly rewarding finding was that the capability to obtain best-in-class coverage as curtain coating raises the possibility of applying low coat weight (5.8 g/m²) in LWC with high coverage (85 %), even at low coating solids (54 %); or, at a constant coat weight of 5-6 g/m²,

there is almost a 40 % advantage in coating coverage using the curtain coater instead of a metered size press.

This work can be beneficial to paper companies in two main ways: first, by defining a compelling value proposition to utilize curtain coating in LWC; second, by implementing startup and operation of the new curtain coating process.

Triantafillopoulos is with RohmNova LLC, Akron, Ohio, USA; Grön is with Stora Enso, Publication Paper, Kymenlaakso, Finland; Luostarinen and Paloviita are with Metso Paper Inc., Järvenpää, Finland. Email Triantafillopoulos at nick.triantafillopoulos@omnova.com.



Triantafillopoulos Grön



Luostarinen



Paloviita