Improving basis weight uniformity with deckle wave control

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A novel equipment development can greatly reduce the deleterious effects of deckle waves on paper machine productivity and paper quality.

Deckle waves are responsible for many paper quality defects, but these defects have been reduced by a device that virtually eliminates deckle-wave generation. It eliminates the waves by containing the stock at the edges of the fourdrinier to reduce thinning with minimal stock surface disturbance.

On a fourdrinier board machine, a dilute fiber suspension, typically 2–4 in. thick, exits from the headbox slice and impinges onto a moving fabric. At the edges, the suspension will spread laterally unless it is contained. Previous attempts to contain the stock and prevent wave generation at the edge included a deckle strap consisting of an endless rubber belt, approximately two inches square in cross section, which traveled with the forming fabric to contain the stock (*1, 2*). This arrangement prevented boundary layer development and reduced surface wakes, but as machine speeds increased it became difficult to keep the strap on its supporting pulleys.

Deckle straps were replaced by deckle boards, stationary flat plates attached to the headbox and sealed to the wire with flexible rubber strips. Deckle boards contain the stock relatively well but are susceptible to buildups of fiber, which eventually break loose. These clumps of fiber can cause sheet breaks. Since the deckle board is stationary, the stock drags along its surface, producing a boundary layer of slower-moving fluid. The slower-moving fluid locally increases stock thickness and displaces flow toward the center of the sheet, producing uneven cross-direction (CD) basis weight profiles.

With the advent of polymeric forming fabrics, it is possible to curl the forming fabric at the edges to contain the stock. Brass wires were not resilient enough to curl; so wedge-shaped blocks (*2*) or mechanical rods are used to curl up the edge of polymeric forming fabrics. However, at each block, there is a tendency for a wave to form due to sagging fabric between the blocks.

The Fab-Curl block was introduced to prevent the wire from sagging (*1*). A continuous, long block is set under the fabric to turn up the edge. Stock is contained at the edges, and machine cleanliness is enhanced, improving runnability.

A common current practice is to contain the stock with a deckle board for the first 1–3 ft downstream from the headbox. Fabric curling devices usually follow this short deckle board. When the stock reaches the end of the deckle board, it spreads laterally until it reaches the curled fabric. Without a mechanism for energy dissipation, this lateral spreading is reflected into the bulk flow in the form of a surface wave, which can cause significant CD weight variation. Papermakers have attributed considerable lost production and lower paper quality to these deckle waves (*1–3*).

To provide better fiber dispersion for improved sheet formation, lower headbox consistencies are being employed in paper machine operation. This approach requires greater slice openings and greater volumes on the fourdrinier with more potential for spreading. For larger slice openings, control at the edges is more critical to maintain acceptable basis weight profiles.

Basis weight variations near the edge of the web can reduce machine productivity. The high spots in basis weight due to large, reflected deckle waves can appear on the reel several feet from the edge. The localized high spots are sometimes cut out of the finished reel at the rewinder. If the deviations are near the edge only, then several extra inches may be trimmed at the couch or winder. For severe deckle waves the reel may be trimmed and cut into rolls which avoid the region associated with the waves. This selection process may result in the loss of several additional inches or an entire roll position, greatly reducing machine production. This type of loss cannot be tolerated in a competitive market.

We have developed a new system to contain the stock and dampen deckle waves (*4*). A deckle blade is used in combination with a curved, fabric edge support. The boundary layer that forms along the deckle blade is partially bled off to reduce the propensity to form waves. The stock that is bled off is reintroduced to the edge of the bulk flow several feet downstream to reduce lateral spreading at the end of the blade. The net result is improved CD basis weight profiles.

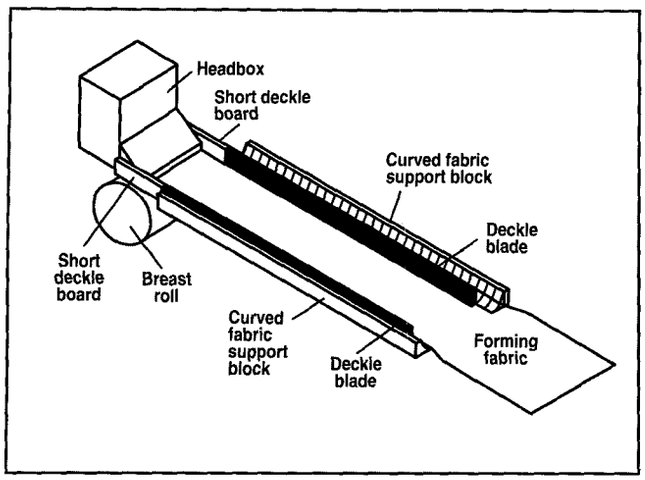
Discussion

Equipment description

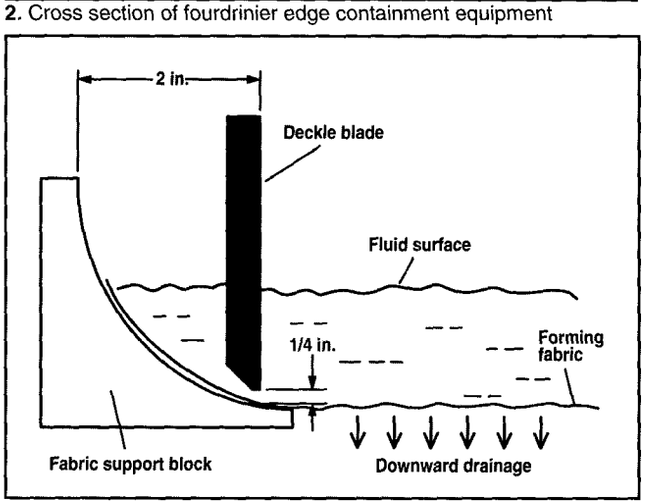
Our edge containment equipment has been designed to control the lateral spreading of stock on a fourdrinier without generating significant surface disturbances, such as deckle waves (*4*). **Figure 1** is a schematic representation of this novel

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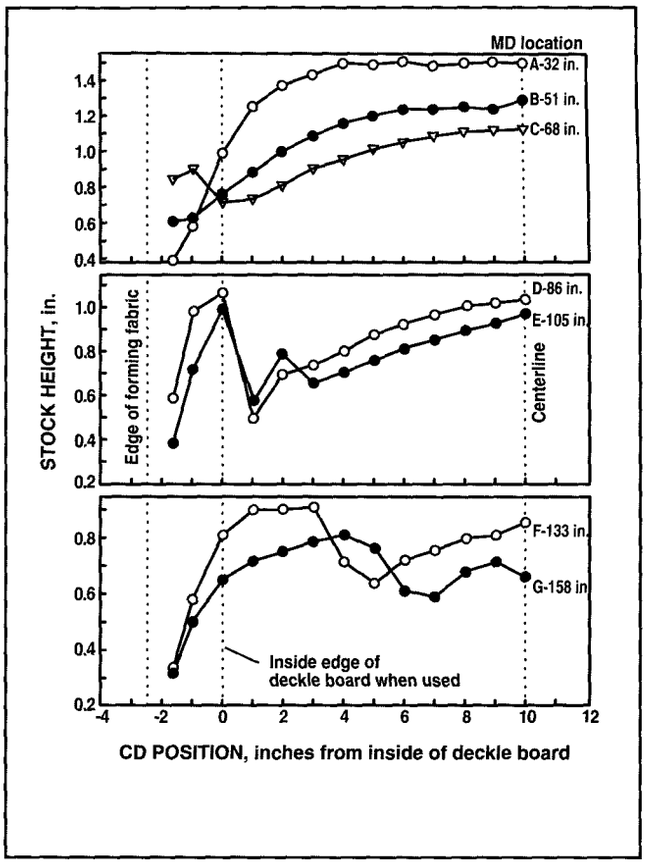
1. Schematic of fourdrinier edge containment equipment



2. Cross section of fourdrinier edge containment equipment



3. CD stock height profiles at 1200 ft/min with a 2-in. slice opening and no deckle blade, taken at several MD locations



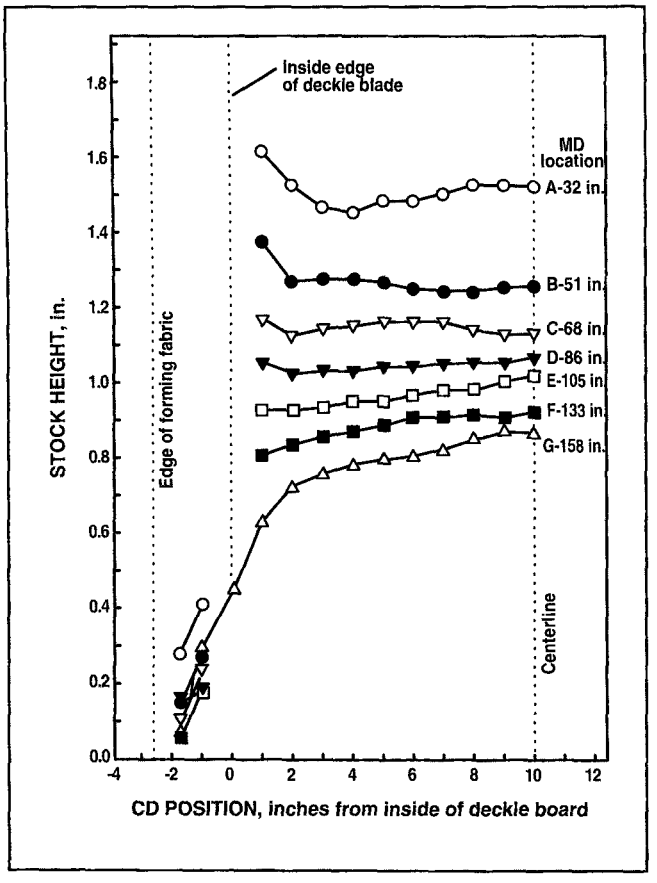
equipment. A short deckle board is attached to the headbox sidewall. Approximately six inches to one foot downstream from the headbox, a solid curved fabric support is used to curl the outer 2–3 in. of the wire. Inside of the fabric support, a polymeric blade continues from the short deckle board. This blade is adjustable horizontally and vertically. The blade is positioned to leave a gap of approximately 1/4 in. between the wire and the bottom of the blade (**Fig. 2**). The upper inside surface of the fabric support block is two inches beyond the inside surface of the deckle blade. Stock bleeds under the blade, gradually filling the channel formed by the outside edge of the blade and the fabric support block. The stock in this channel recombines with the bulk flow when the blade ends. The reintroduction of stock after the blade provides a resistance to lateral spreading. The fabric support generally runs slightly past the end of the blade. Cleaning water flows through the blade support and down the sides of the blade to reduce stock buildup along the blade faces.

Pilot machine trials

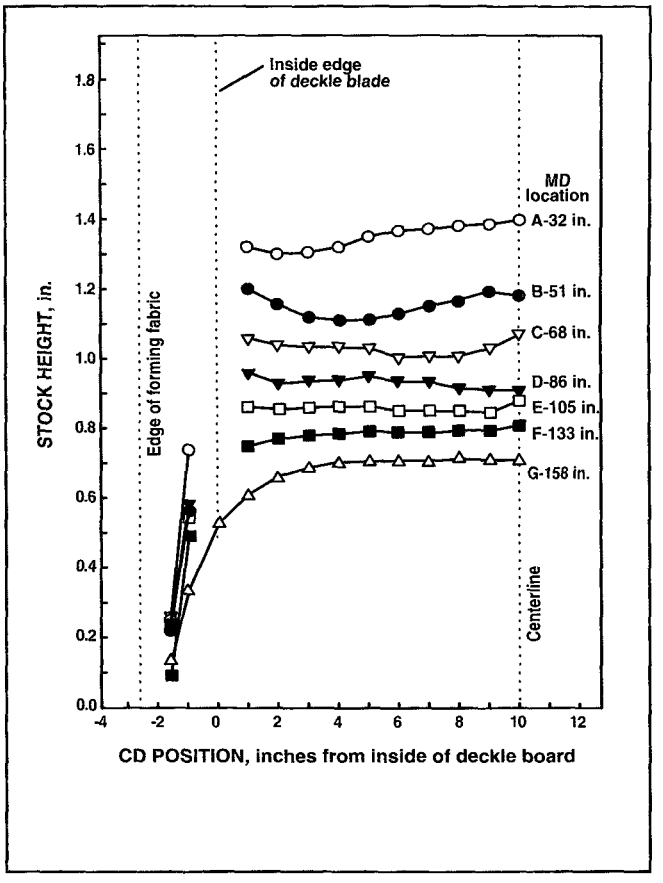
Development experiments for deckle wave control procedures were conducted using a pilot fourdrinier web former at Westvaco's research center in Covington, VA. The headbox slice width is 20 in., and the forming fabric width is 25 in. A machine speed range of 600–1200 ft/min was employed with headbox slice openings of 2 in. and 3 in. Headbox consistency was typically 0.8% for the 2-in. slice opening and 0.5% for the 3-in. slice opening. Cross-direction stock height profiles were determined at several locations down the machine using an NDC gamma gauge. Results are reported for three blade positions: the blade raised completely out of the stock, the blade positioned 1/16 in. above the wire, and the blade positioned 1/4 in. above the wire. The blade was only repositioned on one side. The blade on the other side was positioned to minimize deckle waves for all trials. For this narrow pilot machine, severe deckle waves from one side can affect the entire CD profile.

The objective of these experiments was to develop a procedure to reduce visible surface waves and consequently improve the CD basis weight profile. Additional desirable characteristics for the procedure can include stability over a wide range of speeds and basis weights, simple installation and operation, and enhanced cleanliness on the edge of the fourdrinier.

4. CD stock height profiles at 600 ft/min with a 2-in. slice opening and deckle blade 1/16 in. above wire



5. CD stock height profiles at 600 ft/min with a 2-in. slice opening and deckle blade 1/4 in. above the wire



Results

Figures 3–5 show CD stock height profiles from the centerline (10 in. CD) to the upper inside face of the solid curved fabric support (–2 in.). As the stock moves down the fourdrinier, drainage decreases the stock height. Short deckle boards were mounted flush with the forming fabric and extended from the headbox 18 in. downstream. When used, the deckle blade extended from the short deckle board to a position 138 in. downstream from the slice. Profiles were measured at seven machine direction (MD) positions: 32 in., 51 in., 68 in., 86 in., 105 in., 133 in., and 158 in. from the slice.

Figure 3 shows the CD profiles with the blade raised completely out of the stock for a 2-in. slice opening and a wire speed of 1200 ft/min. The upper profile (A) is 14 in. past the end of the short deckle board. With no deckle blade to contain the fluid, lateral spreading occurs (to the left) until containment by the curled fabric support (–2 in. CD). The second and third (B and C) profiles show the fluid beginning to accumulate along the curled right-hand edge (–1 in. to –2 in. CD). Fluid continues to build in the 0 to –2-in. CD region for profiles D and E and then begins to move back toward the center of the machine, as shown in profiles F and G, as a reflected deckle wave. The amplitude of the wave in profile F is approximately 20% of the initial flow from the slice.

Figure 6 shows the position of the crest of the deckle wave as a function of MD position for 600 ft/min and 1200 ft/min, with a 2-in. slice opening, and for 600 ft/min with a 3-in. slice opening. The deckle blade was not in contact with the fluid. In Fig. 6, the inside edge of the short deckle board is located at 0 in. CD. Positions to the left of the inside edge are in the region of the curled fabric edge. The slice lip is located at MD position 0, and the short deckle boards extend 18 in. downstream. The effect of slice opening is shown by comparing the 2-in. and 3-in. slice openings at a constant speed of 600 ft/min. The lateral speed of the wave is proportional to the square root of the fluid height. For a 3-in. slice opening, the deckle wave crest moved 10 in. toward the center after approximately 96 in. in the MD. Decreasing the slice opening to 2 in. reduced the wave velocity. The combination of lower overall height and dewatered stock resulted in a 50% increase in MD distance for the wave crest to advance 10 in. toward the center. Dandy rolls or top-wire formers will freeze the wave at the CD position it had entering these units. For a faster machine speed at a given slice opening, the wave will travel less toward the center for a given MD position, as shown in Fig. 6.

The deckle blade can be positioned 1/16 in. above the wire without danger of damaging the wire. This blade position is comparable to a conventional deckle board. The inside face of the blade at CD position 0 is located as a continuation of the short deckle board 10 in. from the centerline of the pilot fabric. Figure 4 shows stock height on the wire due to development of the boundary layer along the inside face of the blade in CD profiles A, B, and C. A small amount of stock bleeds under the blade over

its length but not enough to prevent significant stock spreading at the end of the blade, as shown in profile G, taken 20 in. downstream from the end of the blade. At position G, the stock height decreases from the centerline toward the edge of the web. This difference in height causes lateral spreading and a small reflected deckle wave farther downstream (not shown).

When the deckle blade is placed approximately 1/4 in. above the wire (Fig. 5), the amount of stock passing under the blade is greatly increased. The dip in the stock height in CD profiles A and B in Fig. 5 results from the stock bleeding under the blade. The boundary layer along the blade is still present, but it is much thinner. The increase in stock height is smaller along the face of the deckle blade, compared to the previous set of profiles, with very little boundary layer removal (Fig. 4). Very little lateral spreading occurs at the end of the blade where the stock that is bled under the blade is recombined with the bulk flow. The CD profile after the blade (G) is essentially flat for positions 3–10 in. from the deckle blade. Although the actual surface of the stock was essentially level near the edge, the stock thickness decreased toward the edge in profile G due to the contour of the curled fabric (Fig. 2).

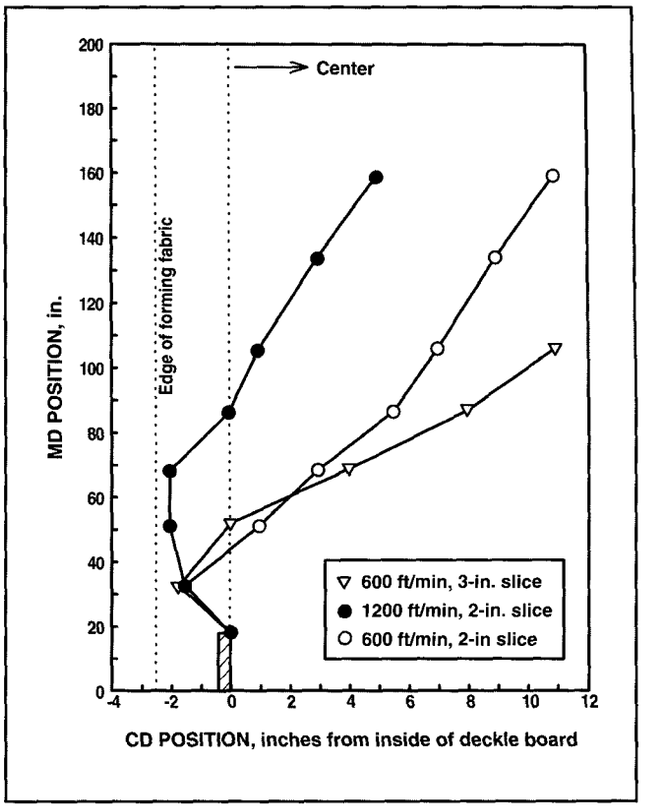
Figures 7 and 8 show the dramatic reduction of the deckle wave accomplished by proper positioning of the deckle blade in the stock. A gap of approximately 1/4 in. between the forming fabric and the bottom of the blade was adequate to suppress the wave. In both cases, the blade on the left-hand side in the photograph on the left was raised out of the stock, which produced a reflected deckle wave. The web is moving from the bottom to the top of the photograph. Figure 7 shows the deckle wave reduction for a 2-in. slice opening at a speed of 800 ft/min. Figure 8 shows a severe deckle wave produced with a 3-in. slice opening at 600 ft/min. The wave is virtually eliminated by proper positioning of the deckle blade. For the 3-in. slice opening, wake generation from boundary layer development is visible when the blade is partially submerged in the stock. However, these surface disturbances dissipate shortly after the end of the blade. For all these photographs, the deckle blade on the right-hand side of the fourdrinier was positioned to minimize deckle wave generation.

Commercial machine trials

The deckle control equipment was installed on a commercial machine. Headbox slice openings were adjusted from approximately 2–4 in. for wire speeds ranging from 700 ft/min to 1800 ft/min. **Figure 9** shows photographs before and after installation of the deckle control equipment for an intermediate-weight product. The edge of the fourdrinier appears on the right with the web moving from the bottom to the top. The reflected deckle wave moves from the right toward the center of the photograph taken before the equipment modification. The wave was eliminated by the deckle blade arrangement. A slight wake is visible just downstream from the blade on the edge in the photo on the right, but it dissipates rapidly. For most installations, showers would be required to reduce buildup along the blade face.

The equipment was installed on a second commercial machine, operating with slice openings ranging from 1.8 in. to 2.8 in. for wire speeds from 600 ft/min to 1100 ft/min. **Figure 10** shows photographs taken before and after the installation of the deckle control equipment. The edge of the fourdrinier appears on the right side of both photos, with the web moving from the bottom to the top. In the photograph on the left, a deckle wave begins at the bottom as indicated by the arrow. This reflected deckle wave was virtually eliminated with the deckle control equipment, as shown in the photograph on the right. **Figure 11** shows CD basis weight profiles for a medium-weight product taken before and after the installation. Near the edges, deckle waves cause the steep gradients in the profile. The CD weight variation at the front and back edges is 40–50% lower after installation of the deckle control equipment.

6. Position of wave crest after 18-in. deckle board with curved fabric support but no deckle blade

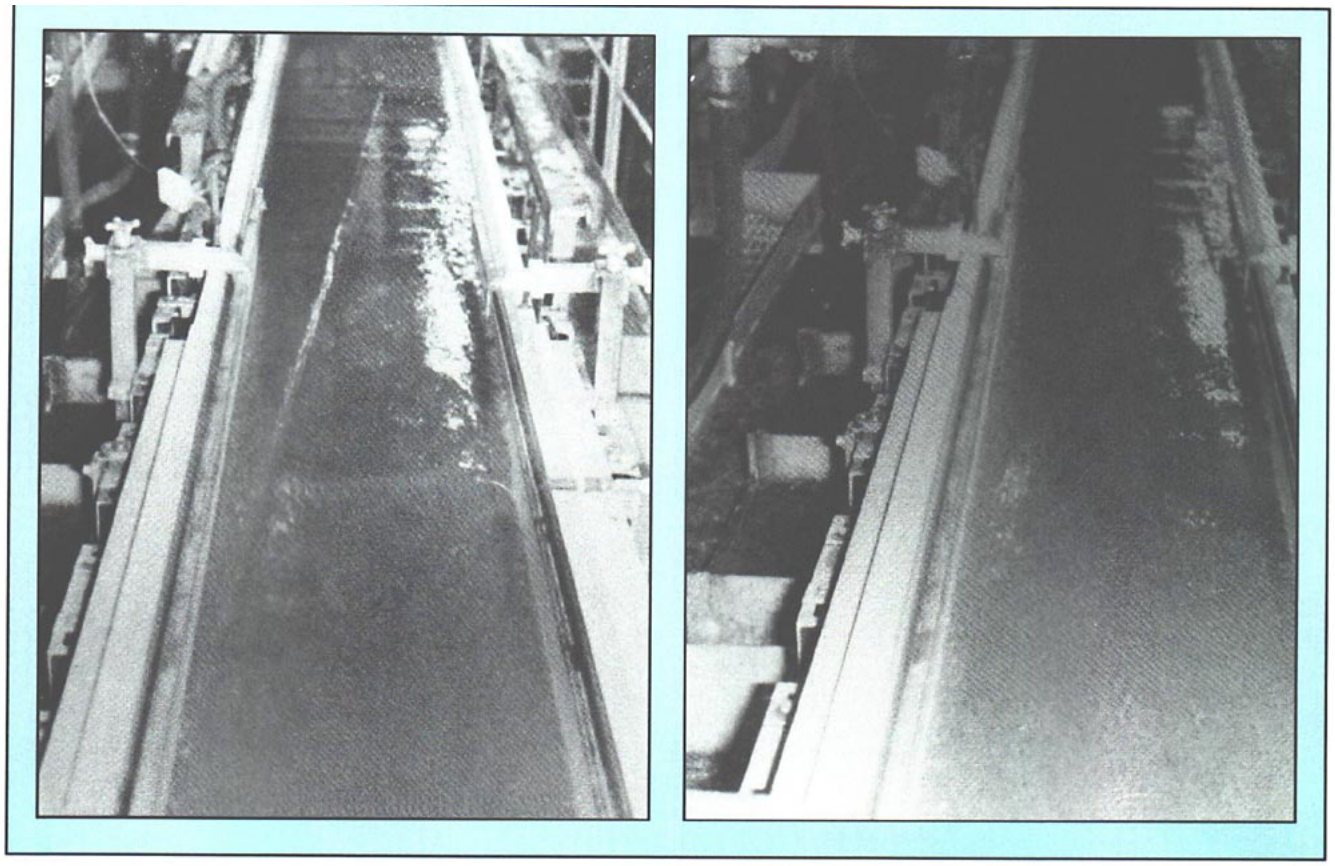


Theoretical background

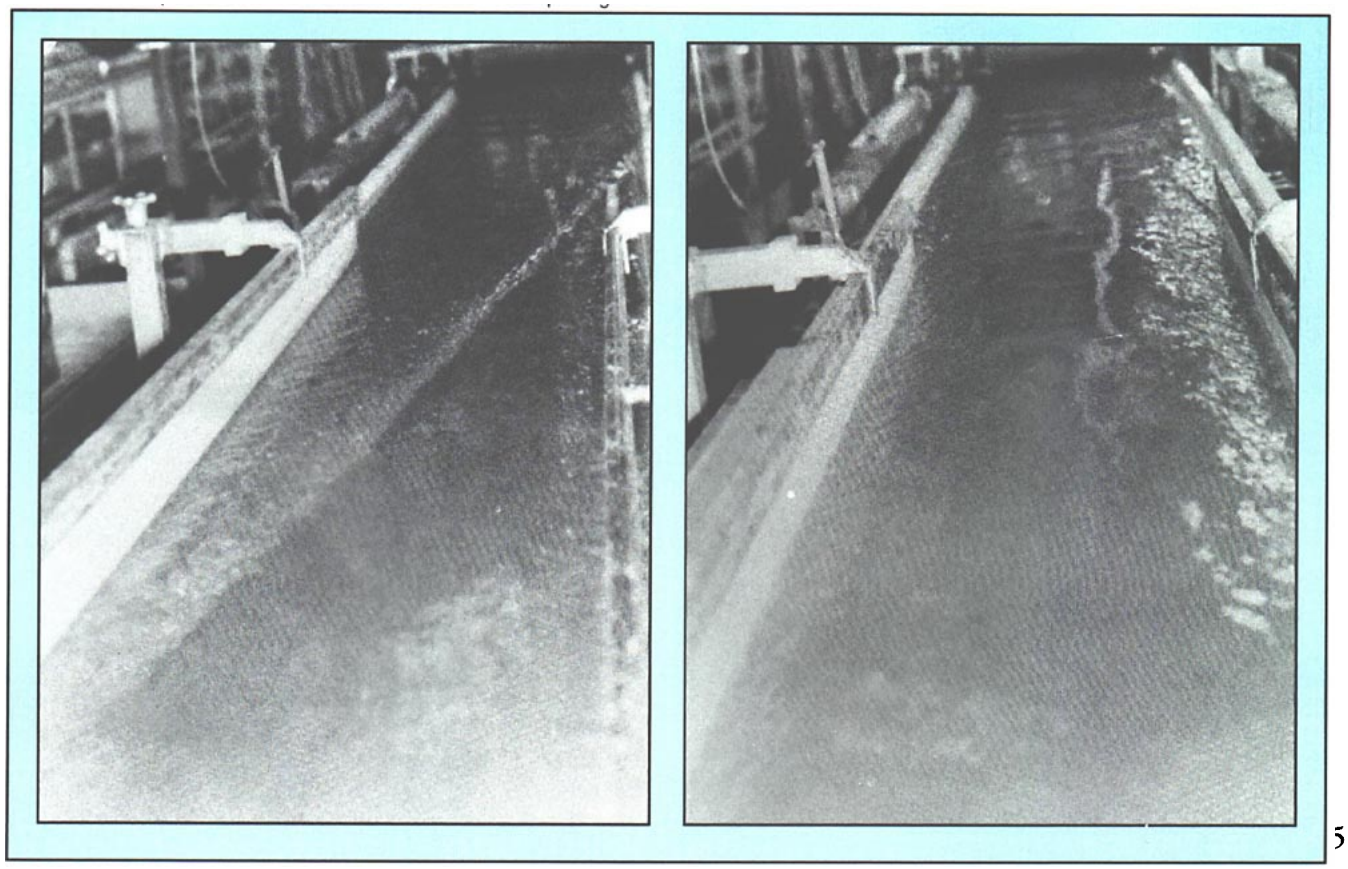
Disturbances are generated on the free surface of the stock near the edge of the fourdrinier by two major phenomena: wakes from boundary layer development and reflection of lateral spreading.

Deckle wave generation and control are affected primarily by machine speed, slice opening, and edge control devices. The slice opening dictates the height of fluid to be contained. The height of fluid is the driving force promoting the initial lateral spreading. For slice openings less than one inch, deckle waves are typically not a major concern. Machine speed affects turbulence, development of the boundary layer, and propagation of waves and wakes. The hydrodynamic prin-

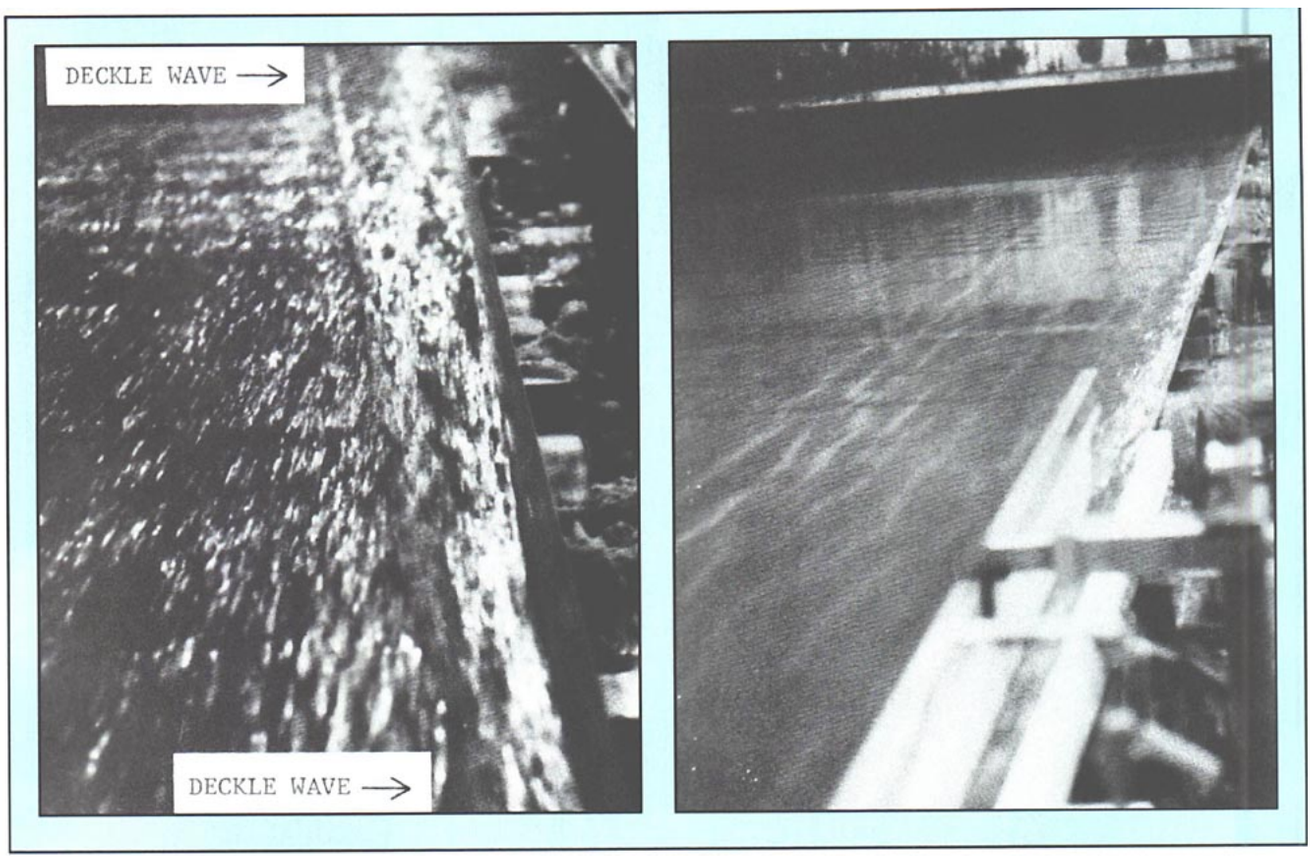
7. Deckle wave pilot trials at 800 ft/min with a 2-in. slice opening



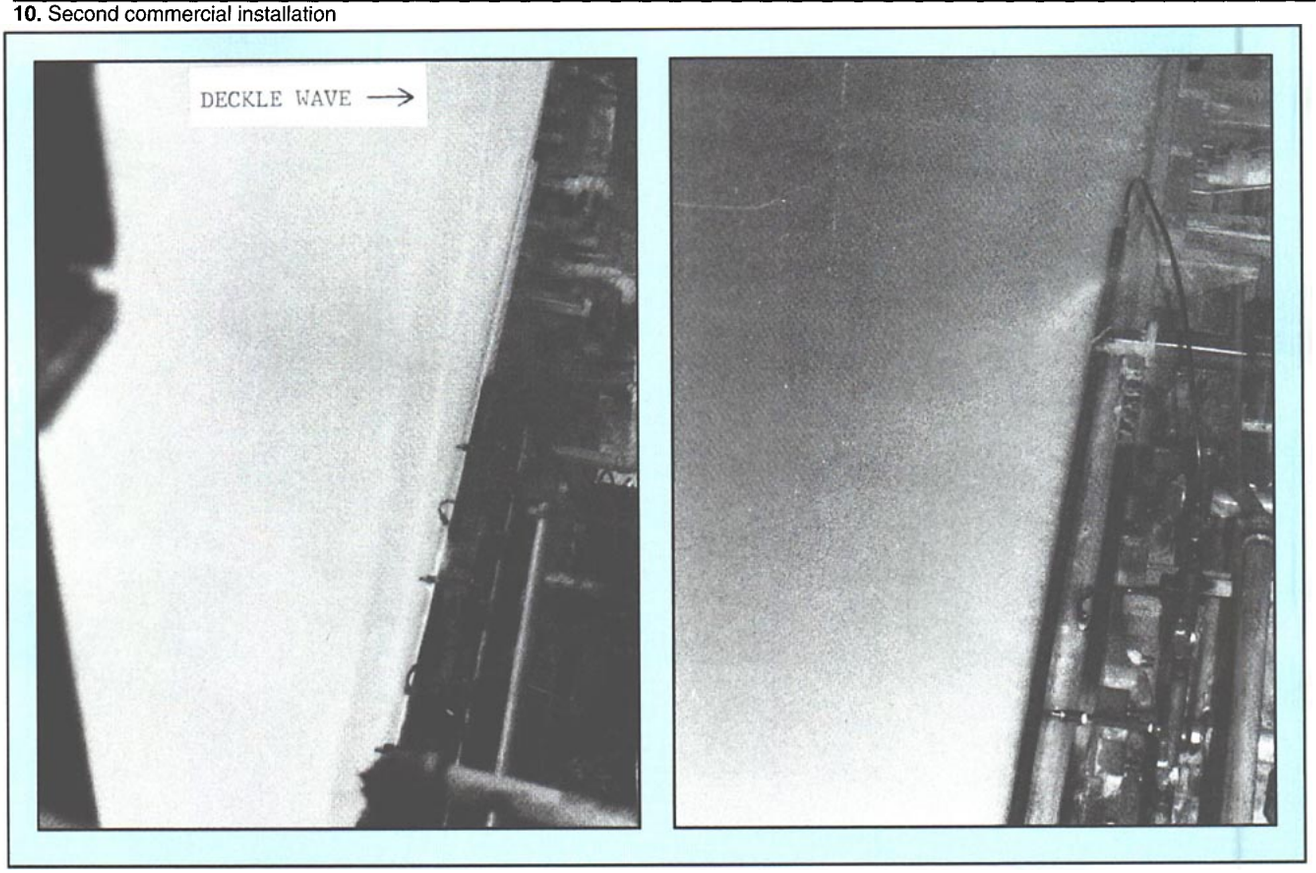
8. Deckle wave pilot trials at 600 ft/min with a 3-in. slice opening



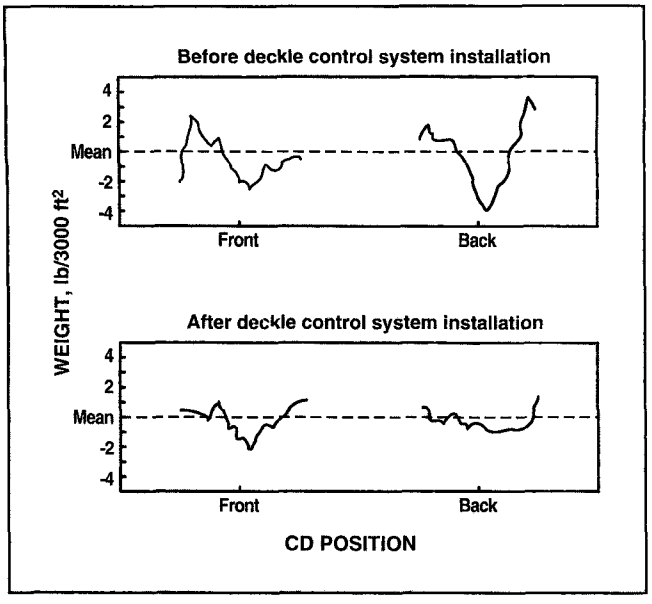
9. First commercial installation



10. Second commercial installation



11. CD raw-stock basis weight profiles before and after second commercial installation of deckle control system



ciples related to flow along the deckle boards are discussed below.

Boundary layer development. Due to the no-slip condition where a fluid contacts a solid, a velocity gradient is created with zero velocity at the wall and the bulk velocity at some distance from the wall. The thin layer next to the wall, where the velocity in the direction of the flow (u_x) is less than 99% of the bulk velocity (U_∞), is defined as the boundary layer (*5*). As the fluid moves from the leading edge of a wall downstream, the boundary layer thickness (δ) increases continuously. Equations to describe the development of the boundary layer under a variety of conditions have been compiled by numerous researchers (*5–7*).

For flow along a flat plate, the boundary layer thickness (δ) is described by Eqs. 1 and 2 for laminar and turbulent flow, respectively:

$$\delta = 5x[(U_\infty x)/\upsilon]^{-1/2} \quad (1)$$

$$\delta = 0.37x[(U_\infty x)/\upsilon]^{-1/5} \quad (2)$$

where

U = bulk velocity

x = location in direction of bulk flow

υ = kinematic viscosity ($\upsilon = \mu/\rho$)

The distance by which the external streamlines are shifted due to the formation of the boundary layer is the displacement thickness (δ_1), which is given by $\delta/8$ for the turbulent flow condition typical of a board fourdrinier.

After 10 ft at 600 ft/min, the boundary layer thickness grows to approximately 1.5 in. At higher speeds, the boundary layer is thinner. The boundary layer grows along the length of the deckle board proportionally to $x^{4/5}$. For long deckle boards, the boundary layer can be a significant source of deckle waves. The streamlines in the vicinity of the deckle board are displaced away from the wall as the boundary layer develops. The lateral velocity component causes movement of stock toward the center of the web.

Suction applied through a restraining surface can reduce the turbulent boundary layer thickness (*5*). On the fourdrinier, bleeding the stock under the deckle blade removes some of the boundary layer. The lateral movement of stock away from the blade toward the center of the web is diminished by providing some flow under the blade.

The flow rate under the blade is a function of the gap between the bottom of the blade and the forming fabric, and the difference between the stock heights inside and outside the blade.

As the stock moves down the fourdrinier, the stock height inside the blade decreases due to drainage, while the stock height in the channel outside the blade increases due to outward flow under the blade. There is no drainage through the fabric support block in the exterior channel. As the difference in stock heights decreases, the flow under the blade diminishes. When the stock heights are equal, there will be no net lateral flow under the blade. Proper selection of the blade–fabric gap produces comparable stock heights on both sides at the end of the blade to prevent subsequent lateral spreading. Natural dissipative mechanisms for flow under the blade provide a means to dampen fluid oscillations and a reflected wave.

Surface disturbances. Along the surface of the deckle board a boundary layer develops perpendicular to the blade. Because of the lower velocity in the boundary layer near the wall, the height of the stock along the wall is elevated slightly. This elevation becomes the driving force for a lateral displacement along the surface of the stock toward the center of the web. The speed of this displacement is given by $(gz)^{1/2}$, where z is the stock height and g is the gravitational acceleration constant (*7*).

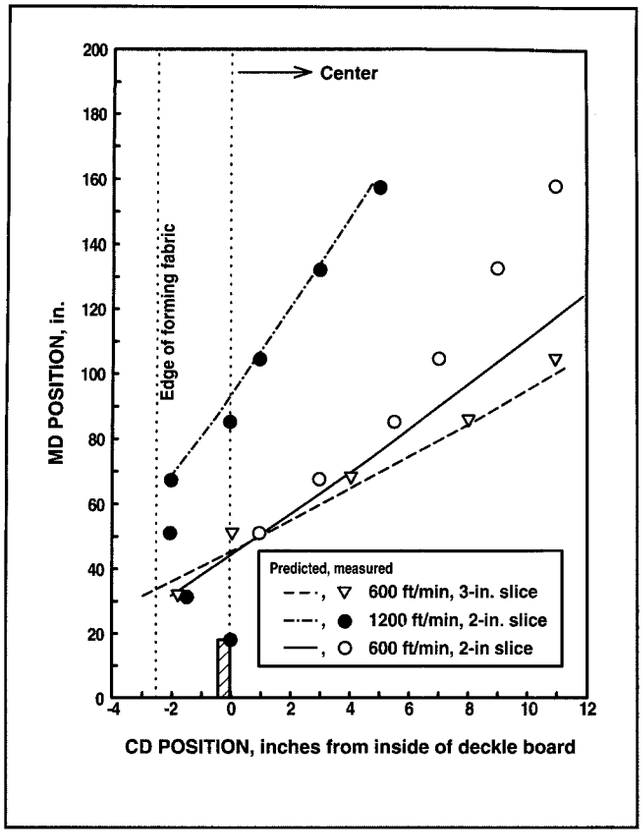
Figure 12 shows measured and predicted wave crest positions for several surge waves caused by reflection of lateral spreading. As the stock drains, the stock height decreases, and the lateral movement of the wave slows, which makes the path of the wave crest appear to curve as it moves down the fourdrinier. Near the edge of the web, soon after the wave begins to move toward the center of the web, the wave follows the predicted path. After the wave crest moves several inches toward the center, observed lateral speeds were slower than predicted. The fiber mat forming on the fourdrinier reduces the height of free liquid. Thus, the fluid height that is the driving force for the wave is less than the measured total stock height.

When the stock reaches the end of a deckle board, it spreads laterally if not contained. This spreading is analogous to the dam break problems (*7, 8*) where a gate is suddenly removed from a frictionless horizontal channel with fluid depth z_0 on one side of the gate and no fluid on the other side. The lateral velocity at any section, u_y, is given by Eq. 3 (*7*):

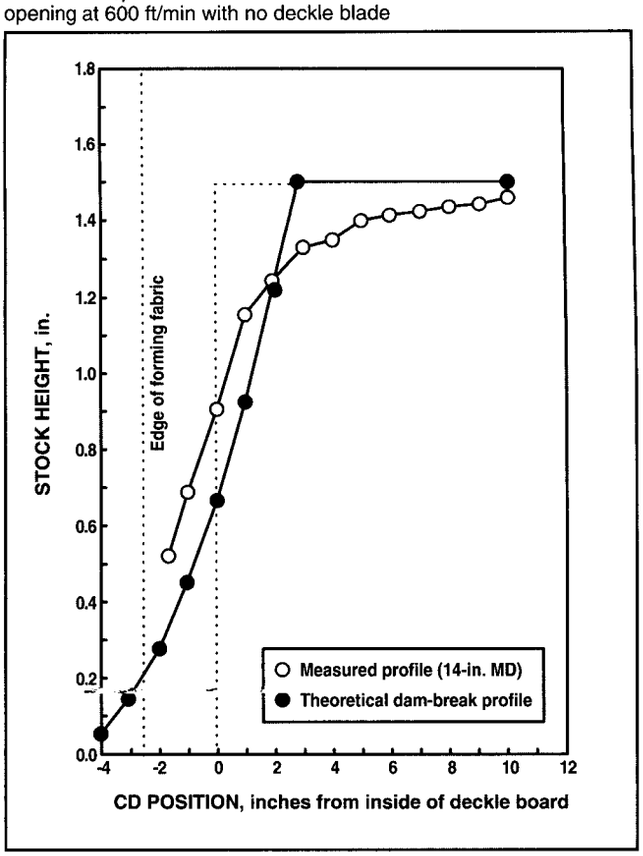
$$u_y = -2(gz_0)^{1/2} \quad (3)$$

The leading edge of the wave (where $z = 0$) feathers out and moves at a speed of $2(gz_0)^{1/2}$. For the frictionless case, the surface profile at time t is described by Eq. 4 (*7*):

12. Predicted and measured deckle wave crest position after 18-in. deckle board with no deckle blade



13. Lateral spread of fluid after short deckle board for a 2-in. slice opening at 600 ft/min with no deckle blade



$$y = [3(gz)^{1/2} - 2(gz_0)^{1/2}]t \quad (4)$$

At $y = 0$, the fluid height stays constant at $4/9\, z_0$. **Figure 13** shows a predicted and an observed stock height profile for lateral spreading just past a deckle board. The surface profiles have essentially the same shape, but the friction along the bottom of the actual wave front prevents the feather edge predicted by Eq. 4. On the fourdrinier, when the wave front reaches the curved fabric support, the kinetic energy is converted to potential energy in the form of increased stock height (Fig. 5). The potential energy is then converted back to kinetic energy as a reflected deckle wave. This reflected wave travels back through the bulk fluid as a surge wave, as shown in Fig. 12.

Conclusions

A device has been developed that greatly reduces the magnitude of deckle waves. A deckle blade, positioned as an extension of a short deckle board, in conjunction with a solid curved fabric support serves to suppress reflected deckle waves and reduce wave generation by boundary layer displacement. The system modification can improve machine cleanliness. Wakes from boundary layer development along the blade are reduced by allowing some fluid to bleed under the blade. In pilot and commercial installations, deckle waves from reflected lateral spreading were all but eliminated. In one commercial installation, CD raw stock basis weight variations near the edge of the web were reduced up to 50%. □

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