PEER REVIEWED

Layer mixing during three-layer stratified forming: the role of vane length and mix-wire speed difference

MIKE D. LLOYD AND BO NORMAN

ABSTRACT

Stratified forming, or the simultaneous forming of a multilayer sheet from a single headbox, can suffer from significant mixing of the different layers. This is holding back the introduction of this technique for the manufacture of printing and writing grade papers. To investigate this mixing, we produced 70 g/m^2 woodfree paper in three layers on an experimental paper machine. The center layer of the pulp was dyed blue to distinguish it and to help ascertain the level of mixing.

Layer mixing caused the resulting paper to have a pattern of blue and white flocs on its surface. The variation of the blue content of the surface within the 0.3–30 mm wavelength range, defined as surface ply variation *(SPV), showed that the heterogeneity of the surface ply was affected by the length of the flexible vanes used to separate the different layers in the headbox, and by the mix-wire speed difference during dewatering.*

Longer vanes in a contracting nozzle meant higher flow velocities, both at the vane tips and in the flow channels, and this was thought to produce more intense and smaller-scale turbulence. This type of turbulence tended to mix the layers more at the fiber level rather than at the floc level. The total formation of the sheets, however, was independent of vane length.

Application:

This paper explains the effect of key process variables on paper quality during multilayer forming.

STRATIFIED FORMING CAN produce a sheet where the different layers are mixed to a greater or lesser extent *(1–7)*. The material from the different layers can be mixed as discrete flocs, as flocs consisting of even mixtures of the two types of material, or somewhere in between these two extremes. In the case where the paper consists of discrete or near-discrete flocs of the two types of pulp, flocs from the different layers can be found in the surface plies of the paper. (To minimize confusion, *ply* will be defined as the position in the formed sheet, i.e., fibers from the center and surface layers can end up both in the center and the surface plies.)

Because of the uneven composition of the paper's surface, it is easy to imagine that if the pulp in the center layer were significantly different from the pulp in the surface layer, the surface ply would be quite heterogeneous and possibly print poorly. This is a major factor that has held back the introduction of stratified forming of printing and writing grades, despite the possibilities that it offers for these grades. Layer mixing can also reduce the benefits to be gained from the extra complication of stratified forming.

In this paper, we describe the methodology and results of some of the trials we have carried out to investigate stratified forming of three-layer paper with a grammage and forming consistency similar to those of the single-layer production of printing and writing grades. Vane length had a significant influence on layer mixing, and we both quantify this influence and advance a hypothesis to explain it.

SOURCES OF MIXING TURBULENCE

Turbulence in a stratified headbox is likely to come from two sources. The first is vane tip vortices *(8, 9)*, which are formed in the wake behind the vane tips. The wake in turn results from the step expansion at the vane tip and the boundary layers in the moving fluid on both sides of the vanes. This produces a characteristic velocity gradient pattern downstream of the vane tips. Lasheras *et al. (10, 11)* suggest that the resulting turbulence in this region has the following structure:

- A system of coherent vortices with their axes in the spanwise (cross) direction
- Counterrotating pairs of streamwise (machine-direction) vortices that are superimposed onto the CD vortices. The MD vortices are formed because of the instabilities caused by the CD vortices and act to link them. MD vortices have a scale smaller than, but are comparable to, that of the CD vortices. Most of the layer mixing is thought to be due to these MD vortices.

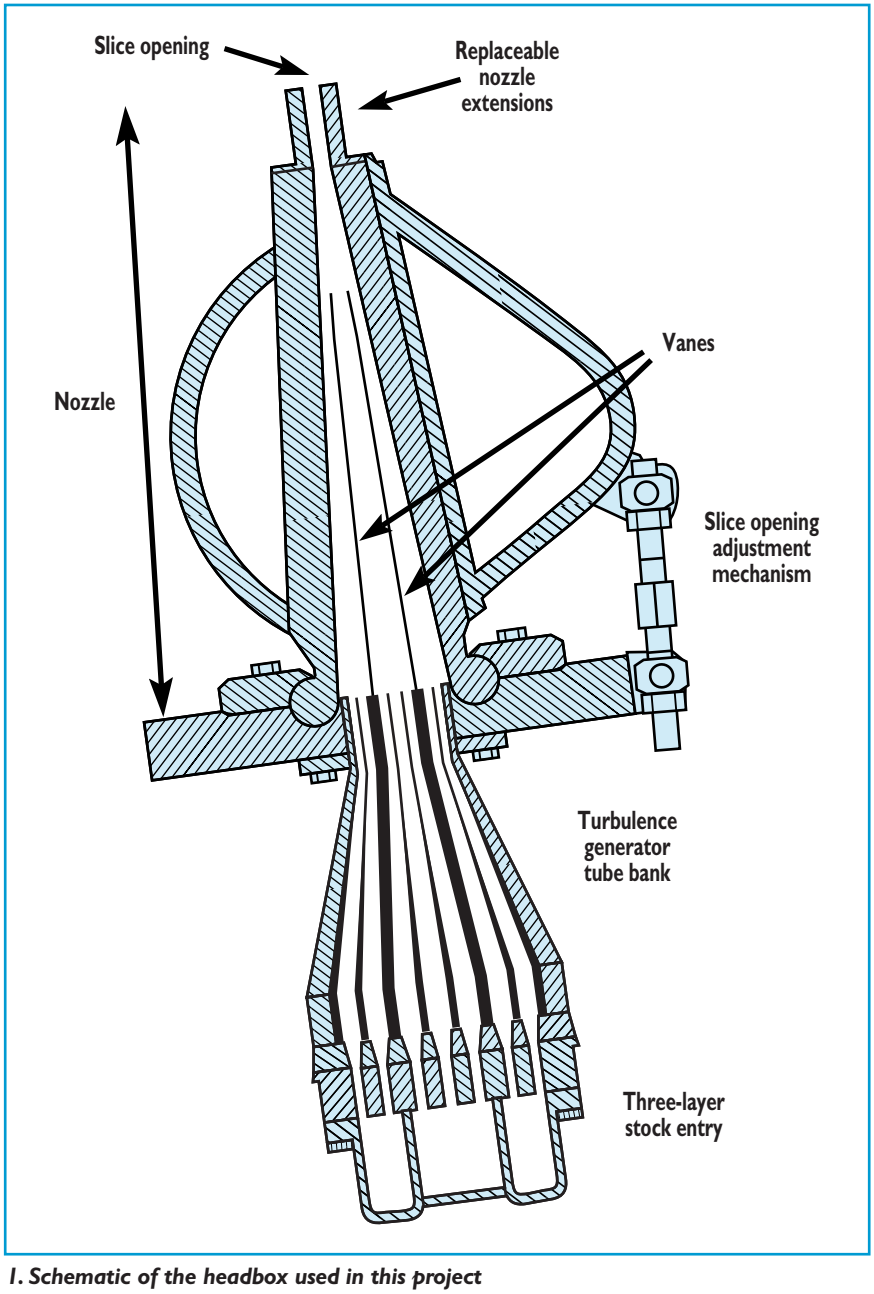
Lasheras and others *(10–12)* have produced experimental, numerical, and schematic visualizations of these vortices with pure Newtonian fluids, but this can only suggest what might happen with a flowing pulp suspension. Because these vortices occur at the boundaries between the different pulp layers, the vortices tend to mix these layers. Since turbulence in

paper forming is thought to be reflected in the flocculation patterns of the formed paper *(13, 14),* the mixing patterns are most likely influenced by the final turbulence patterns produced by the vanes.

A second source of turbulence is that resulting from flow at high Reynolds numbers. While the Reynolds-number concept cannot be directly applied to fiber-containing suspensions because of their highly non-Newtonian flow properties, we can still calculate a Reynolds number for the system assuming the viscosity of water. With vanes the same length as the nozzle, a flow rate of 13.3 m/s in the 3.7 mm wide outer-layer flow channel gave a Reynolds number of about 50,000, suggesting a very turbulent flow. This level of turbulence may even be understated with a fiber suspension, as fibers increase the rate of momentum transfer through a suspension *(15)* (especially in this case, where the channel thickness is similar to that of the natural floc size).

In addition to vane tip vortices and channel turbulence, Baker *et al. (6)* have suggested that the flow patterns produced by the tubes of the turbulence generator may affect the patterns of turbulence and that CD flow irregularities, such as those discussed by Aidun and Kovacs *(16),* may also be involved. These effects are not examined in this paper, however, as our pilot paper machine is too narrow (at 330 mm wide) to accurately measure them.

The patterns formed by these vortices are in turn further complicated by additional stresses introduced by hydrodynamic shear between the stock jet and the wire during dewatering, along with pressure pulses such as those in blade forming. In normal forming, these are mostly beneficial, which is why a degree of jet-wire speed difference is often used to improve formation.

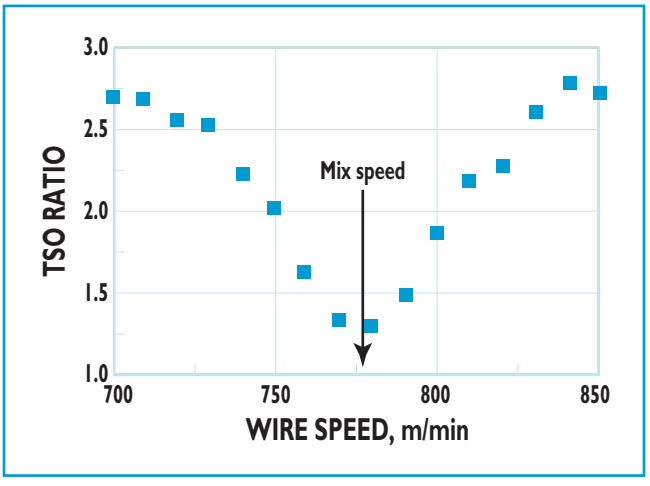


1. Schematic of the headbox used in this project

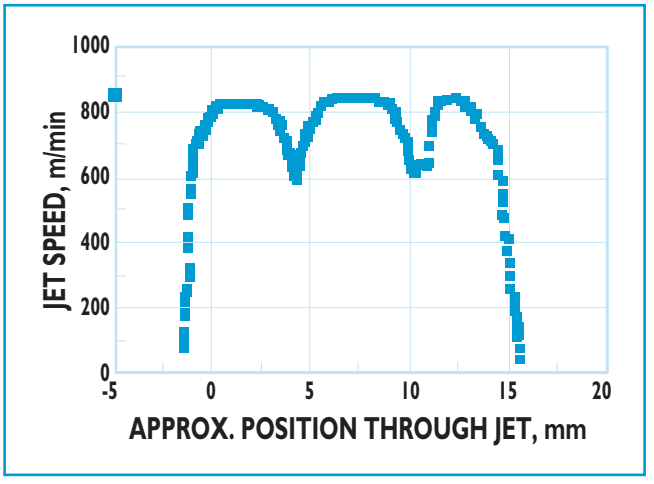
CHARACTERIZATION OF LAYER MIXING

The *z*-direction ply purity of a multilayer sheet has traditionally been measured by splitting the sheet into a number of layers (plies) in the *z* direction and measuring the amount of the layer components in the different plies. Examples of measured components include kraft vs. mechanical fibers, or filler content *(1, 3, 4, 6, 17–19).* While such tests give meaningful information, they ignore the fact that the components from the different layers can exist in discrete flocs, and hence there can be a patterned or random distribution of components in the MD and CD directions in each *z*-direction ply. This means that the measured value for ply purity will be a poor predictor of the local ply purity at any given position in the sheet.

An alternative technique is to stain one or more of the layers with a permanent dye and study the resulting distribution of dyed and undyed fibers. In our case, we stained the



2. Example of a plot of TSO ratio vs. wire speed used to estimate the mix speed. The relative vane length (RVL) was –250 mm in this case.



3. Recorded velocity profile almost immediately downstream of the vane tips. The relative vane length was +20 mm. Jet speed calculated from pitot tube pressure.

center layer with a light blue dye to distinguish its final position in the sheet. This resulted in a sheet with a mottled appearance due to a mixture of blue, white, or mixed blue and white flocs being seen on the surface. This mottled appearance was retained even when the sheet was split.

MATERIALS AND METHODS

Forming of stratified paper

Stratified paper was made on the Swedish Pulp and Paper Research Institute's (STFI's) FEX pilot paper machine *(20).* Two short-circulation loops were used, one for the center layer and one for the outer layers. Mixed white water coming from all three layers was used to dilute the thick stock flows. The white water system was closed with a disc filter. Pulp was not recirculated after forming.

The headbox was a 330 mm wide, three-layer stratified headbox with the general configuration shown in **Fig. 1.** The turbulence generator had seven tube rows, split into three banks of two/three/two rows. The tubes began as 12.9 mm-ID pipes, which lasted for 90 mm before a step expansion to a 24 mm diameter. After this, there was a smooth transition over a 420 mm length to the 28-mm (CD) by 11.5 mm *z*-direction (ZD) rectangular outlets. The tubes at the outlet had 2 mm thick dividing walls (CD and ZD), while the three banks of tubes were separated by two 14 mm thick vane-mounting areas. The two outer banks of tubes were each spaced 6 mm from the top and bottom of the nozzle. The results reported in this paper were recorded using a nozzle with a linear convergence from a 130 mm upstream ZD width to a 15 mm slice opening over an MD distance of 730 mm.

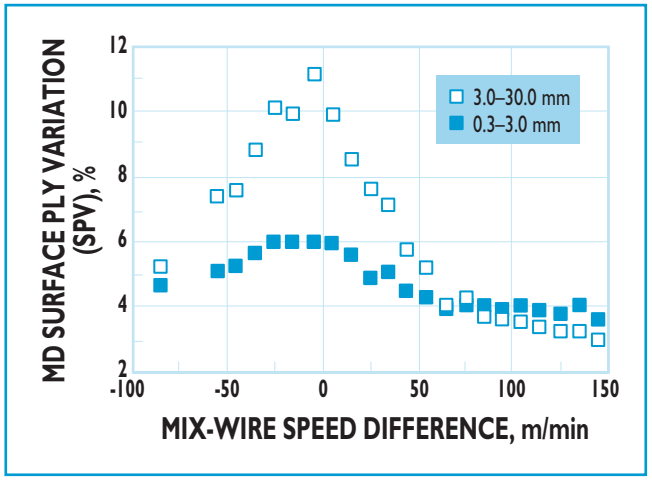
Pulp entered the headbox in three different layers and was separated by 1.5 mm thick polycarbonate vanes. The final (downstream) 50 mm of the vanes was tapered on the outward-facing surface to a 0.5 mm final thickness. The vanes were reasonably flexible and free to move to an equilibrium position.

Since we thought that the distance between the vane tips and the nozzle opening was more important than the absolute length of the vanes, we defined vane length relative to the nozzle opening. As an example:

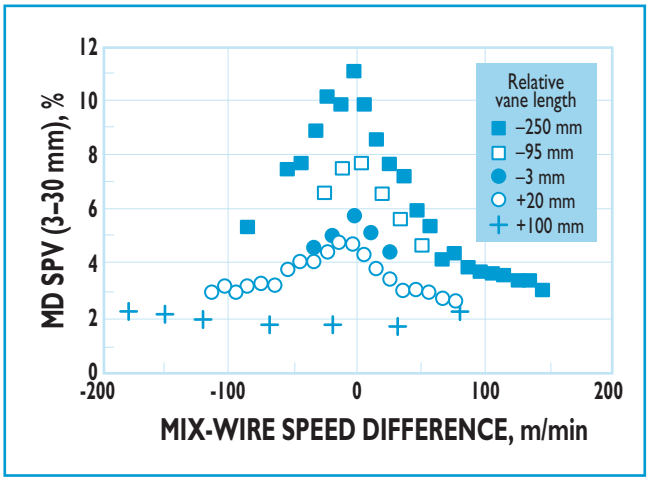
- A –250 mm relative vane length (RVL) meant that the vane finished 250 mm before the end of the nozzle.
- A +20 mm RVL meant that the vanes finished 20 mm outside of the nozzle.

The same furnish was used in the three layers: a 50% hardwood/50% softwood bleached kraft pulp mixture. The two pulps were separately refined to a freeness of 25 (±1) SR° with specific edge loads of 1.0 and 1.5 W·s/m, respectively. The only difference between the layers was that 7 L/ton (ovendry fiber) of Ciba-Geigy Pergosol Tuerkis F-2G light blue dye was added to the center layer to distinguish it.

All of the results shown were collected with the dewatering in a pure roll-forming mode *(21),* as this has a lesser effect on sheet structure than roll-blade forming *(22).* The nominal roll wrap was 70°. The 1635 mm diam. forming roll had a vacuum zone divided into three parts *(21);* these zones had circumferences of 16.5°, 21.5°, and 26.5° and vacuum levels of 3, 3, and 10 kPa, respectively. The forming wires were normal fine paper wires at a tension of 6 kN/m. Trials were done using a fixed jet speed of approximately 800 m/min, and a range of wire speeds centered around 800 m/min. The free jet length between the headbox and the dewatering nip was about 250 mm. The stock consistency was



4. Effect of the mix-wire speed difference on MD surface ply variation. RVL = –250 mm.



5. Effect of relative vane length on large-scale MD surface ply variation

0.5–0.6%, and the first-pass retention was 87–90%. No retention aids or other chemicals were added.

At a wire speed of 800 m/min, the ovendry (o.d.) grammages of the outer/center/outer layers were 20, 30, and 20 g/m^2, respectively. Changes in wire speed led to proportional changes in the grammages of all three layers, but this was allowed for by indexing paper properties *(22, 23).* The paper was dried off-line against a single cylinder at 1.5 m/min under MD and CD restraint.

Paper properties were plotted against the mix-wire speed difference, where *mix speed* is defined as the wire speed at the minimum of a tensile stiffness orientation (TSO) ratio–vs.–wire speed curve (see **Fig. 2**).The *TSO ratio* is the ratio between the length and width of an ellipse representing ultrasound velocities in different planar directions of the paper sheet, as recorded by a TSO meter.The TSO ratio can be related to fiber orientation *(24).*

In this case, mix speed is thought to represent the average speed of the mix during dewatering. The speed difference was used instead of the more commonly cited speed ratio, as Svensson and Österberg *(25)* have shown that it is the absolute speed difference, rather than the relative speed ratio, that affects paper properties.

Measurement of surface ply variation

Traditionally, the evenness of the surface ply has been referred to using terms such as *coverage (7),* which can imply a random distribution of the fibers from the surface layers covering the center layer. However, this distribution is not random and, in fact, can show semistructured patterns. Examples of these are shown in the appendix. Because of this we have introduced the term *surface ply variation* (SPV). SPV was defined as the variation seen in the surface of a stratified formed sheet when one or more of the layers have been dyed.

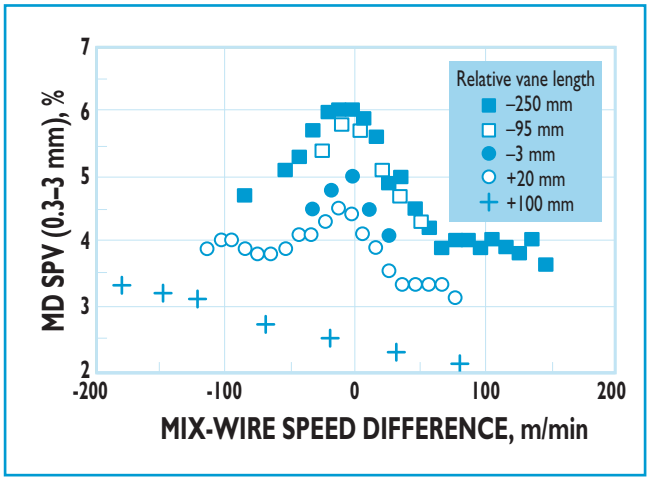
SPV was measured by scanning samples with a photo scanner and then analyzing these images in a way similar to the STFI-formation method. Samples measuring 17.4 x 8.7 cm (MD x CD) had full-color images of their forming-roll-side surface scanned using a flatbed photo scanner at a resolution of 300 lines/in. Power spectrum analyses of these images were used to calculate the coefficient of variation of the cyan content of these images in the 0.3–3 mm and 3–30 mm wavelength ranges. We define these as *small-scale surface ply variation* and *large-scale surface ply variation,* respectively. Both machine and cross directions were analyzed. Higher values meant greater variation, i.e., a more heterogeneous surface. SPV values are affected by the colors and layer grammages used in the experiments, but these were held constant in this trial.

We could estimate the most common floc size from the peak position (dominant wavelength) in the power spectrum. To do this, we assumed that the blue and white flocs had the same average size and that the wavelength of variation represented the average combined length of one blue floc and one adjacent white floc in the direction being measured. Hence, the surface ply floc size was half the value of the wavelength where the power spectrum peaked. This only applied, though, where the power spectrum peak value was greater than 2 mm, as peak wavelengths below this value are unlikely to be due to flocs. Wavelengths below this value probably indicate either a variation at the fiber level or a random distribution.

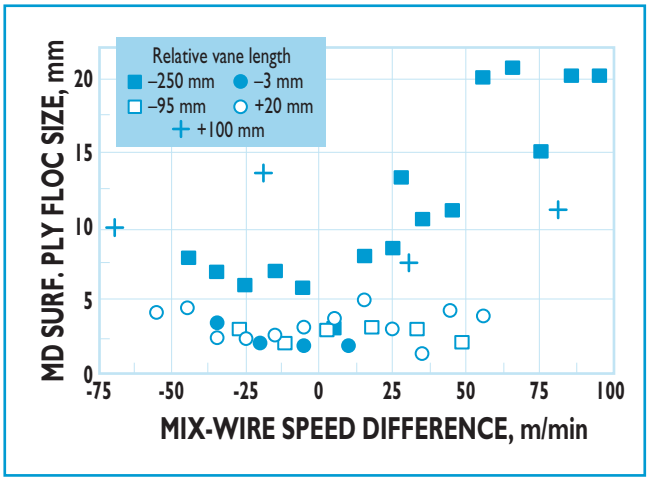
Other testing

Ply (or *z*-direction layer) purity was subjectively evaluated by splitting the sheet into ten 50 x 200 mm (MD x CD) plies using a combination of double- and single-sided adhesive tape (3M Scotch Tape, type 850 4N). By weighing the unsplit paper sample after each ply had been removed, we could estimate the grammage and *z*-direction position of each ply.

Formation was tested according to the β-radiography method originally developed by Norman *(26).*



6. Effect of relative vane length on small-scale MD surface ply variation



7. Effect of relative vane length on MD surface ply floc size

This method has been updated so that the analysis of the x-ray film is done using a desktop scanner / Matlab analysis system similar to that described for the SPV analysis. The formation values were further normalized by dividing them by the equivalent formation values for British Standard handsheets made from each day's pulp. This reduced the influence of pulp quality on formation values. These values were referred to as *BSH-normalized formation numbers* and were given in the 0.3–3 mm and 3–30 mm wavelength bands.

RESULTS

Velocity profile downstream of the vane tips

Figure 3 shows the measured velocity profile almost immediately downstream of the vane tips as measured by a 1 mm ID pitot tube *(27)* with the headbox running pure water. A clear velocity dip corresponding to the position of the two vanes can be seen. Because of the turbulent vortices previously discussed, such a velocity profile quickly disappears downstream, as other experiments, where the pitot tube was farther away from the vane tips, only showed a flat curve, indicating an even velocity profile through the jet. While vortex production can be minimized by making the vane tips as sharp as possible *(5, 9)* and so reducing the width of the velocity disturbance, vane tip vortices can probably never be removed as long as there are boundary layers adjacent to the vanes.

General characteristics of the SPV images

The paper's surface had some interesting features when looked at with either the human eye or the scanner. The formed patterns often consisted of a combination of streaky and scallop-like features. The balance between these two types of patterns was strongly affected by the difference between the mix and wire speeds, as is demonstrated in the appendix.

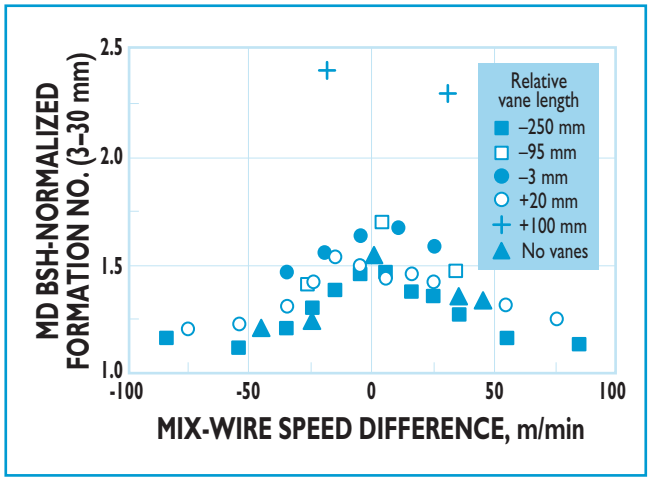
The material from the different layers can be mixed as discrete flocs, as flocs consisting of complete mixtures of the two types of material, or somewhere in between these two extremes. In the case where the paper consists of discrete or near-discrete flocs of the two types of pulp, flocs from the different layers can be found in the surface plies of the paper.

SPV spectra plots differed when recorded in the machine and cross-machine directions due to the different forming forces in these directions. In particular, streaking in the MD was seen in some samples; this was recorded as increased values of CD SPV. There were also differences between the two sides of a given sample. This was not surprising, as no forming process is completely symmetrical. However, trends in the SPV on one side of the sample were often echoed on the other side of the sample, especially if only the headbox (and not the forming conditions) was being changed. For this reason, only the SPV data from the inside (with respect to the forming roll) surface were reported in this paper. However, if the forming conditions were changed (e.g., with the addition of blade dewatering), it is important to report the SPV from both sides.

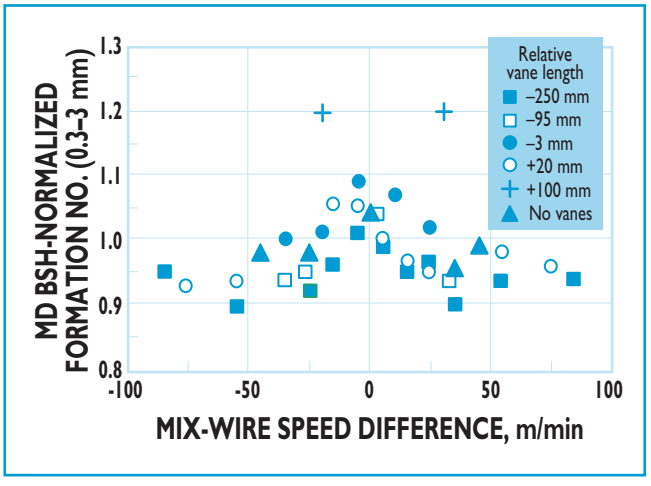
Influence of the mix-wire speed difference

A major factor controlling the SPV was the mix-wire speed difference. The large-scale SPV in particular was strongly affected by the mix-wire speed difference (see **Fig. 4**.)

The SPV was greatest, indicating the most heterogeneous surface, at a mix-wire speed difference of about 0 m/min and decreased with either increased or decreased wire speed, i.e., by running in a "drag" (mix speed < wire speed) or "rush" (mix speed > wire speed) situation. This dependence on the mix-wire speed difference is similar to what was shown by Andersson and Bergström in 1954 for formation *(28)* and has been repeatedly shown since then. However, unlike what is seen with formation results, there were no local minima on either side of the zero speed difference. Instead, within the range of



8. Effect of relative vane length on large-scale MD formation number



9. Effect of relative vane length on small-scale MD formation number

speed differences tested, the SPV continued to improve as the speed difference was increased in either direction. In this case, the local minima in the formation number results occurred at values of about ±60 m/min.

Paper formed with high values of rush or drag was more streaky than paper formed with mix-wire speed differences close to zero, which instead had more of a scallop-like pattern. This suggests that the streakiness in our trials was mostly caused by the mix-wire speed-difference shear dragging out the flocs on the surface of the paper, rather than by a streakiness in the jet caused by a headbox effect.

Effect of vane length

The length of the vanes also had a large effect on the SPV, as shown in **Figs. 5 and 6.** As the vanes got longer, the SPV decreased as the surface ply got more homogenous. This suggested that the problem of high SPV could simply be solved by the use of long vanes. However, sheet splitting revealed that there was a catch with this. Split-sheet samples from the +20-mm paper showed that the flocs in all of the plies were composed of varying mixtures of blue and white fibers. In contrast to this, –250 mm and –95 mm results showed a clear differentiation between the blue and white flocs, i.e., the center layer and surface layer flocs. In the center plies of the –250 mm results, there were more blue than white flocs, and this is reversed in the surface plies.

Hence, the +20 mm results suggested more mixing within flocs, while the –250 mm and –95 mm results showed greater mixing between the flocs, with the ply impurity coming from the mixing of the flocs from the different layers. The extreme case of mixing at the fiber level occurred with the +100-mm vanes, where it was difficult to distinguish between the two types of fibers in the sheet surface.

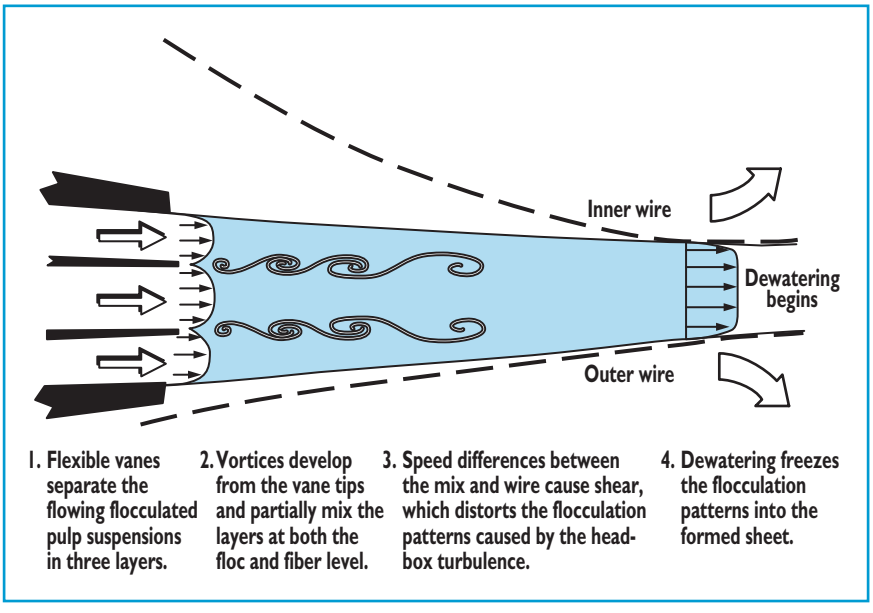
It is also useful to study the surface ply floc size. **Figure 7** shows that the shortest vane, –250 mm RVL, produced the largest floc size, especially for large positive speed differences. By an RVL of –95 mm, the flocs got considerably smaller, and then the surface floc size did not change with RVL until a value of +100 mm. The +100 mm vanes produced a larger-scale pattern, but this is misleading as the surface plies consisted of blue and white fibers that were almost completely mixed.

Another trend in Fig. 7 was that the –250 mm RVL results were sensitive to the mix-wire speed difference, but the –95 mm to + 20 mm results were not. The reason why the –250 mm results showed this sensitivity is that the flocs tended to be stretched by the speed-difference shear during dewatering. In contrast to this, the flocs from the –95 mm to +20 mm results instead appeared to be more broken up by this shear, giving peak wavelengths of less than 1 mm, which was considered to be random variation.

Formation results

Large- and small-scale formation number results are given in **Figs. 8 and 9.** In both wavelength ranges, the vane length had little consistent effect, apart from the very bad formation produced by the +100 mm vanes, especially in the large wavelength range. The latter was not surprising, as the jet was clearly very turbulent and diverged in the *z*-direction once past the vane tips. There is an extra data series shown in these graphs, i.e., the formation number results with no vanes in the headbox. Removing the vanes did not alter the formation, confirming that in these conditions, the sheet formation was in most cases independent of vane length.

It is interesting to note that small-scale formation was better than that of British Standard (BS) handsheets made from the same pulp for mix-wire speed differences of less than ±50 m/min (small-scale formation number < 1), despite the much greater pulp consistencies used in paper machine forming. This is probably due to Wrist's self-healing effect *(29),* which would be assisted by the speed difference—which would increase fiber mobility. Both Norman



10. Schematic of suggested forces during roll dewatering of a stratified formed three-layer sheet

et al. (30) and Sampson *et al. (31)* have shown that this self-healing effect is stronger at smaller wavelengths and that flocculation dominates at larger wavelengths.

DISCUSSION

The different factors thought to affect the evenness of the surface ply are summarized in **Fig. 10.**

A hypothesis for the effect of vane length

The reduction in SPV with increasing vane length had two forms:

- A reduction in surface ply floc size up to a relative vane length of ~95 mm, but with the flocs principally consisting of fibers from only one of the layers (high floc purity)
- A reduction in floc purity for vanes longer than this but with the surface ply floc size no smaller than about 2 mm.

A hypothesis for this result is that an increase in vane length leads to a change in the scale and intensity of the turbulence in the headbox. To understand this better, it is useful to consider turbulence as a combination of eddies spinning in different directions, with each eddy having its own scale and intensity (or velocity). Turbulence energy is transferred from larger eddies to smaller eddies, which dissipate this turbulent energy through viscous drag and viscoelastic work on the pulp fibers. Hence, the average eddy size is a function of the total turbulent energy, with greater turbulence energy giving a smaller average eddy size *(15)*. The scale of turbulent eddies is limited by the dimensions of the system, so in a turbulence generator, the maximum eddy size is the internal diameter of the turbulence generator pipes.

Turbulent eddies are capable of breaking up pulp flocs if they are strong enough, but as the turbulence decays, transient flocs quickly re-form *(14)*. The size of the resulting flocs is thought to be affected by the average size of the eddies *(13, 15, 32)* in the flowing fiber suspension at the moment of floc formation. Steen *(33)* suggested that flocs smaller than the average turbulent eddy size will be combined by the eddies, while flocs larger or similar in size to the turbulent eddy will be eroded and then broken down by the turbulent eddies. Once the turbulence intensity is less than that of the pulp network strength, the turbulence will cease to affect this network.

It is likely that the structure of both the vane tip vortices and the channel turbulence was affected by where the vanes tips finished. As the vane tips got longer, the flow channels became narrower, leading to both faster flow rates and smaller flow dimensions. Higher flow rates will mean steeper velocity profiles near the vane and headbox wall surfaces, increasing the levels of turbulence. Hence, the turbulent vortices (or eddies) coming off the tips of longer vanes would be expected to have more energy and possibly be smaller than those coming off the tips of shorter vanes. In contrast to this, the channel turbulence eddies and vane tip vortices created by the shorter vanes, which finished in a wider part of the nozzle, were possibly too large and too weak to break down the incoming flocs, and instead only mixed them.

The vane length effect will be amplified by the effects of the remaining nozzle contraction after the vane tips. Reiner and Wahren *(34)* suggested that headbox contraction damps the level and decreases the scale of the turbulence. With shorter vanes, there is an opportunity for this turbulence damping, but not with the longest vanes.

The smaller and more intense turbulence created by the longer vanes is more likely to have broken down the incoming flocs into their individual fibers, which then re-formed into flocs with fibers from other layers. The resulting 2–4 mm floc size was unstretched by any mix-wire speed difference, similar to that suggested by the formation spectra of the same samples, and probably represented an equilibrium floc size for this particular pulp/headbox/forming system. Alternatively, this may be the "minimum dominant floc size," which was thought to be insensitive to increasing levels of turbulence [as discussed by Parker *(15)*].

CONCLUSIONS

A combination of vane tip vortices and channel turbulence is thought to cause significant mixing of the different layers during stratified forming. The vane tip vortices are thought to come from a wake effect downstream of the vanes. The channel turbulence is caused by high flow rates in thin channels. This turbulence led to mixing at either the floc or fiber level. The resulting pattern of flocs from the different layers in the jet was then affected by the mix-wire speed difference during forming, which, in some but not all cases, can cause streaking of these flocs.

The length of the flexible vanes separating the different layers had a large effect on the type of mixing. Shorter vanes led to mixing at the floc level, while longer vanes produced mixing at the fiber level. This was thought to be due to an increase in the intensity and a decrease in the scale of the turbulence with longer vanes, due to the resulting narrower and hence faster flow channels where the vanes finish.

Very long vanes caused complete turbulent mixing of the different layers and very poor sheet formation. Otherwise, formation did not appear to be significantly affected by vane length. We noted that the small-scale (0.3–3 mm wavelength range) formation for these roll-formed sheets was similar to that of BS handsheets made from the same pulps, suggesting that forming conditions were more important than forming consistency at this scale. The large-scale (0.3–30 mm wavelength range) formation was about 1.5 times worse than that of comparable BS handsheets. **TJ**

Lloyd was a guest researcher at the Swedish Pulp and Paper Research Institute, S-114 86 Stockholm, Sweden. His permanent affiliation is with PAPRO New Zealand, New Zealand Forest Research Institute, Private Bag 3020, Rotorua, New Zealand. Norman is a professor at the Royal Institute of Technology, S-100 44 Stockholm, Sweden.

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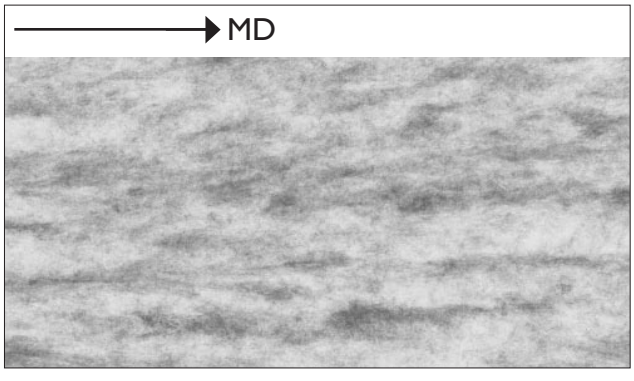
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APPENDIX

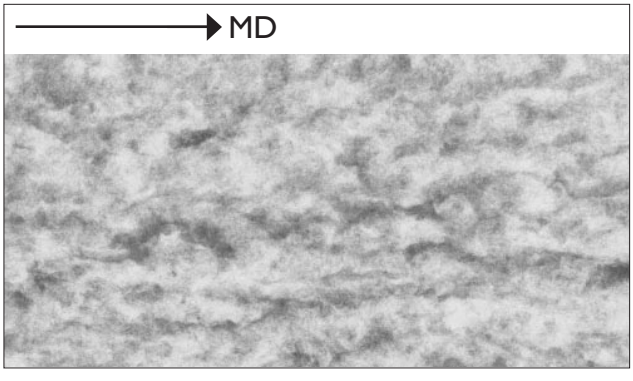
Surface ply variation images

Figures 11–16 show the surfaces of six sheets of paper along with their forming conditions. These are the images used for calculating SPV, i.e., a full-color image has been recorded and broken down into its cyan, magenta, yellow, and black components, and all except the cyan have been discarded. Each image represents the negative of the final image, so a darker tone indicates more whiteness.

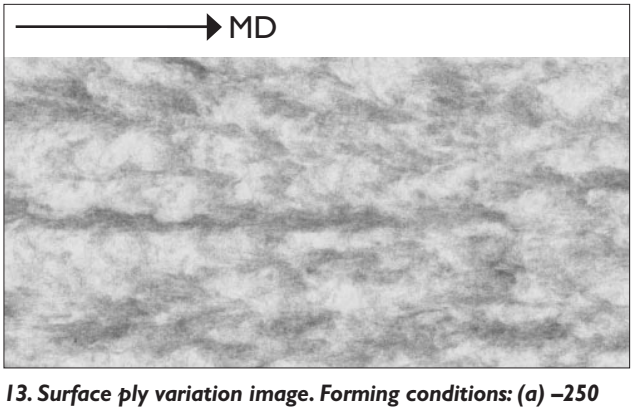
Note that the –250 mm RVL results show a greater unevenness and are more sensitive to speed difference than the +20 mm RVL results.



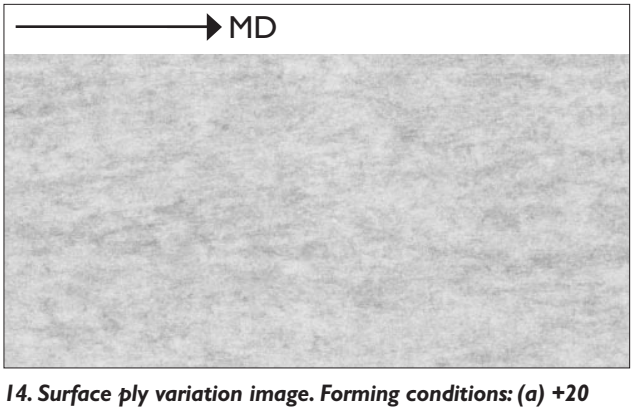
11. Surface ply variation image. Forming conditions: (a) –250-mm relative vane length and (b) +35 m/min mix-wire speed difference.



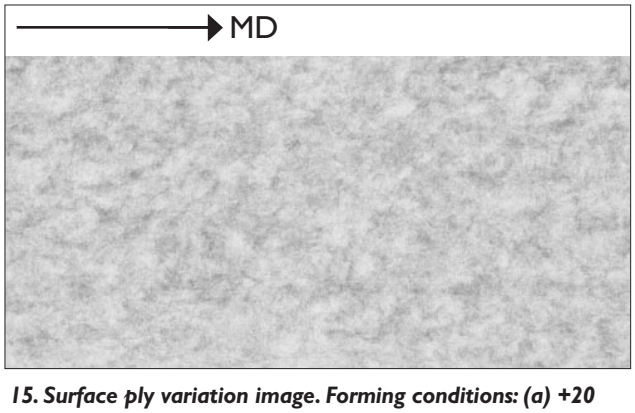
12. Surface ply variation image. Forming conditions: (a) –250 mm relative vane length and (b) +5 m/min mix-wire speed difference.



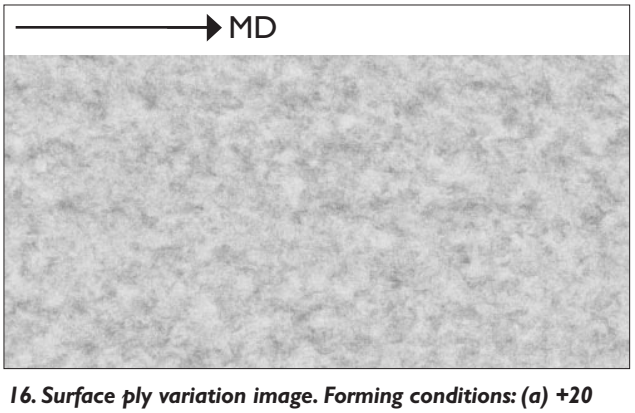
13. Surface ply variation image. Forming conditions: (a) –250 mm relative vane length and (b) –35 m/min mix-wire speed difference.



14. Surface ply variation image. Forming conditions: (a) +20 mm relative vane length and (b) +35 m/min mix-wire speed difference.



15. Surface ply variation image. Forming conditions: (a) +20 mm relative vane length and (b) +5 m/min mix-wire speed difference.



16. Surface ply variation image. Forming conditions: (a) +20 mm relative vane length and (b) –35 m/min mix-wire speed difference.