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REDUCTION OF LAYER MIXING IN STRATIFIED FORMING THROUGH HYDRODYNAMIC CONTROL

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ABSTRACT

STFI-Packforsk has recently patented the "Aq-vanes", a new technology for stratified forming headboxes. In this new solution, a thin passive liquid layer (a liquid vane or "Aq-vane") is injected in the headbox between neighbouring pulp streams through a narrow hollow channel, thereby preventing mixing between the layers.

One of the most interesting features of the Aq-vane technology is that layer purity and separation can be controlled externally by tuning a set of process parameters. This opens the field for a widespread industrial application of stratified forming, a paper-maker's quantum leap that may reduce energy and raw material consumption, lead to improved product properties and possibly even to the development of new grades. In fact, although the basic concept of producing an engineered layered structure is not new in papermaking; its application has been extremely limited to a few selected grades, such as high grammage paperboard or multi-layer tissue.

The Aq-vanes have been implemented on EuroFEX, STFI-Packforsk's research paper machine, for extensive pilot scale trials. Thereby a number of technical solutions for the injection of the liquid layer has been tested and evaluated. In a parallel project, a method for measurement of layer purity in stratified forming has been developed. It is based on sheet splitting using a

heat-seal pouch lamination technique. An image analysis method is then used to identify the colour of the fibres and thus the layer mixing.

INTRODUCTION

Contrary to multi-ply forming stratified forming produces a layered structure with one single headbox. This is not a new concept in the papermaking industry and several publications have appeared in the scientific and technical literature since the 1970's. The reason for this long-going interest is the potential large potential; see *e.g.* Bergström and Peel (1979) [1], Johnsen (1984) [2], Harwood (1989) [3], Häggblom-Ahnger (1998) [4], Tubek-Lindblom and Salmén (2002) [5].

Stratified forming can be applied to paper grades of any grammage. Its industrial potential resides in the same set of considerations as presented in the late 1970's by Bergström (1979) [6] and Bergström and Peel (1979) [1]. In their analysis, they classified the potential advantages of stratified forming into aspects connected (*i*) with an improvement of the economy of the papermaking process and (*ii*) the design of new paper grades.

Stratified forming has been industrially implemented for the production of two specific products, two-ply liner and tissue products. However, there is only one installation for printing papers, see Begemann (1998) [7].

The most important obstacle on the way towards a wider industrial implementation of stratified forming is due to the unacceptable degree of mixing between neighbouring pulp layers. Layer mixing is due to the fundamental hydrodynamic processes in the wakes that are formed at the point were the pulp streams are brought together.

Background

Flexible headbox vanes are often mounted in modern paper machine headboxes. These are usually present to give a more isotropic paper sheet but could also be used for stratification (layering). In addition, the presence of vanes can dampen vortex generation after the tube bank, which can prevent streaks originating from the headbox.

The research regarding stratified forming has been both experimental and numerical. The simulations performed by Farrington (1991) [8], included one headbox design with flexible separation vanes, and the result was a strong effect on turbulence behaviour after the tips of these vanes. Baker et al (1995)

[9] performed experiments with headboxes aimed at stratified forming. The results clearly showed that the vanes initiated strong secondary flows. It was argued that the strong streak-creation, which could be visualised by individual colouring if the layers, is a result of three-dimensional flows after the vane-tips.

Parsheh and Dahlkild (1997) [10] numerically studied the mixing behind vanes with different tip shapes and positions using flow simulations. These were performed with the k-ε turbulence model with a geometry similar to that of Lloyd and Norman (1998) [11], who performed a study where the optimal vane length was identified. In the simulations by Parsheh and Dahlkild, which were two-dimensional, the mixing was studied by adding a passive scalar into one of the layers. The spreading of this scalar was then studied. Their results showed that the shortest vane gives the lowest mixing at a relevant distance downstream in the jet.

Lloyd and Norman (1997) [12] performed experimental pilot machine trials aimed at stratified forming on the EuroFEX at STFI. The experiments were conducted by forming a paper sheet with a 3-layer headbox where all layers consisted of the same stock, but the middle layer was coloured blue to visualise the layer mixing. Three headbox slice geometries in combination with different vane lengths were tested. A parrot's beak slice lip was compared to a linearly converging slice lip and a plane channel slice lip. The results showed that with the vanes ending inside the nozzle, the parrot's beak appeared to reduce layer mixing, while the parallel channel appeared to increase it. However, the type of slice lip had little effect on layer mixing if the vanes ended outside of the headbox; vane tip vortices then seemed to be the dominating source of mixing. The parrot's beak also improved the small-scale formation.

Finally, Lloyd and Norman (1999) [13] studied the effect of vane shape, primarily through stepped vanes. The aim of the steps was to break down the boundary layers formed upstream along the vanes, and thus reduce downstream vortex generation. However, the turbulence introduced by the steps increased the layer mixing, both at floc and fibre level. This turbulence gave lower fibre orientation anisotropy, worsened small-scale formation and Z-toughness, but improved fracture toughness of the formed sheets.

Söderberg (1999) [14] performed a pilot machine study of the effect on contraction on headbox jet flow, a study not specifically aimed at stratified forming. In the study, the same stratified headbox as that of Lloyd and Norman was used. The length of the nozzle and vane was kept constant and the inlet area of the headbox nozzle was varied. Each layer in the headbox was given an individual colour. The headbox was mounted at the fourdrinier position in the EuroFEX pilot machine and the headbox jet was visualised at several MD positions after the slice. These visualisations were compared to the paper produced, which was scanned using an ordinary desktop scanner. The results showed that the characteristics of the jet are reflected in the structure of the paper sheet and that both the low and high contraction headboxes give a strong mixing of the different layers. However, the dynamics behind the mixing seemed to be very different.

Li et al, (2000a) [15] and Li et al, (2000b) [16] studied stratified headbox flow by an experimental technique where salt was added the centre layer and the conductivity profile was measured across the jet thickness. Due to layer mixing, there is a spreading (relaxation) of the measured conductivity profile downstream of the vane-tip and headbox. They investigated the effect of slice opening; jet speed and vane tip position on the degree of mixing. At a given position in the jet, the mixing was reduced at higher slice opening and flow velocity. In addition, they concluded that the main part of mixing takes place in headbox and jet, and not during dewatering.

THE PHYSICS OF LAYER MIXING

The mixing behind a trailing edge (blunt or sharp) is a result of the wake. This wake will always be present because of:

- The thickness of the blunt body (cylinder, plate etc)
- The boundary layers that will develop on the same

For the case of a blunt body, the drag would be severely reduced if the wake did not exist. Hence, the mixing of the wake is directly coupled to the drag on the body, see Roshko (1955) [17]. By implementing the "base-bleed" technique, which is based on blowing out a gas or liquid at the trailing edge, this drag can be lowered, see Wood (1964) [18] and Bearman (1967) [19]. Consequently, this also means that the mixing (turbulent) is reduced. The "base-bleed" concept has been used as a technical solution in many industrial applications, e.g. aeronautics and coating.

For the case of a vane (also called lamella) the blunt-body effect will not be present. However, the boundary layers will be pronounced since they can develop over a longer distance. Hence, there will still be a significant wake at the tip of the vane, which will result in severe mixing even if the vane is infinitely thin.

The Aqua-Vane technique

Conventional separation vanes are flexible but solid structures. This leads to large scale mixing at the end of the vanes as described above. The layer mixing is the result of a fundamental hydrodynamic phenomenon in the wake of the vanes and cannot be avoided even by making the vane tips extremely sharp.

The detrimental effect of the wake can however be reduced by adding a third stream of liquid, Figure 1. A passive thin layer of liquid is injected between the pulp streams through a hollow vane. Small scale mixing between the liquid layer and the pulp flows will still occur, but the large scale mixing between the two pulp layers is significantly reduced.

Thus hydrodynamic control of the layer mixing in stratified forming is obtained by replacing the conventional stratification technique, where thin blades ("vanes" or "lamellas") are used to separate the pulp streams, with a thin passive liquid layer (a liquid vane or "Aq-vane") which is injected between neighbouring pulp streams through a narrow hollow channel. The technical solution has also been patented by STFI-Packforsk (Söderberg, 2003a, 2003b) [23, 24], Figure 1.

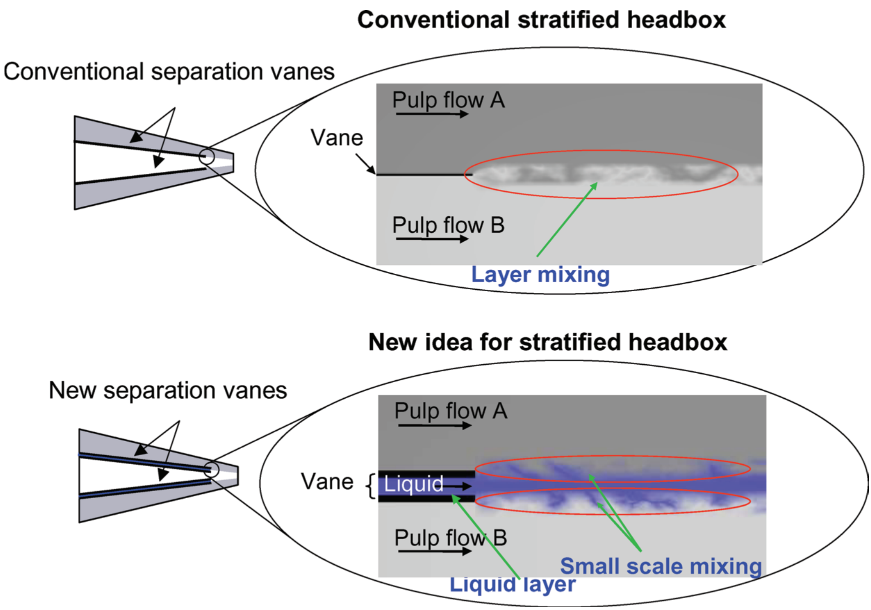


Figure 1 The principle of hydrodynamic control of layer mixing in stratified forming. The technique is called Aq-vanes or Aq-lamellas.

It should be pointed out that part of the technique is to control the flow behind the wake. Thus, it is needed that the speed of the fluid ejected at the trailing edge can be varied independently from the speed of the surrounding pulp suspension.

The principle of injecting something between the layers has been used before. *KMW* manufactured a headbox with vanes that injected air (and the vanes were rigid). However, in order to achieve the base-bleed effect the fluid in between the layers has to have similar density to the surrounding fluid.

Numerical calculations

For the case of a Newtonian fluid, e.g. water, the flow is most likely laminar at the tip of the vane, as shown by Parsheh (2001) [20] with application to papermaking and more generally by Talamelli et. al. (2002) [21]. Since the flow is laminar at the tip it will probably result in von Kármán vortex shedding. This instability is in practice impossible to avoid since it is generated by a so-called global absolute hydrodynamic instability, see e.g. Huerre and Monkewitz (1990) [22]. The well-ordered flow structure that is generated by the shedding will break-down into streaky structures aligned in the flow direction.

Here it is assumed that the flow is governed by the Navier-Stokes equations. Clearly this assumption means that the effect of fibres is neglected as is the effect of turbulence. Based on classical reasoning for headbox flows the Reynolds number is high. Hence the flow is turbulent. In the authors opinion this far from true and, in addition, neglecting the fibres is the most severe simplification.

The flow is assumed to be two-dimensional and governed by the following set of equations.

$$\rho\left(\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y}\right) = -\frac{\partial p}{\partial x} + \mu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) \tag{1}$$

$$\rho\left(\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y}\right) = -\frac{\partial p}{\partial y} + \mu\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) \tag{2}$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{3}$$

Where (1) and (2) are the momentum equations in the x-direction (MD) and y-direction (ZD) respectively. Conservation of mass is imposed by Equation (3), which is the continuity equation.

In these equations, u and v are the velocities in the x- and y-directions respectively (MD and ZD in papermaking terminology) and p is the pressure. In addition, ρ is the density of the liquid (water) and μ the viscosity. By scaling the equations with a suitable velocity U and length-scale h the equations can be written as

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -\frac{\partial p}{\partial x} + \frac{1}{Re}\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right),$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = -\frac{\partial p}{\partial y} + \frac{1}{Re}\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right),$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0,$$

where Re is the Reynolds number, which is defined as

$$\mathrm{Re} = \frac{\rho U h}{\mu}.$$

The Reynolds number is the most used non-dimensional number in fluid mechanics and is used to characterize if the flow is prone to be turbulent. For the present study the characteristic velocity, U, is set to the flow velocity in the headbox at the vane-tip and the length-scale, h, is the thickness of the vane. Generally it is judged that the Reynolds number is of the order of 10^4 for the present study.

The base-bleed principle has been evaluated numerically. This has been done using the *FEMLAB* software and the calculations have been performed in the geometry that can be seen in Figure 2. In the figure the mesh can also be seen.

As inlet boundary conditions the flow inside the Aq-vane is assumed to be fully developed Poiseuille flow and at the outer surfaces of the Aq-vane a boundary layer is prescribed. At the upper and lower boundaries a slip/symmetry condition is applied and as outflow condition the pressure is prescribed. The flow velocity in the headbox (free-stream) is 1.0 at the inflow boundaries. The relation between the flow in the Aq-vane and the surrounding free-stream is characterized by S_u, which is defined as:

$$S_u = \frac{U_{Aq}}{U_\infty}.$$

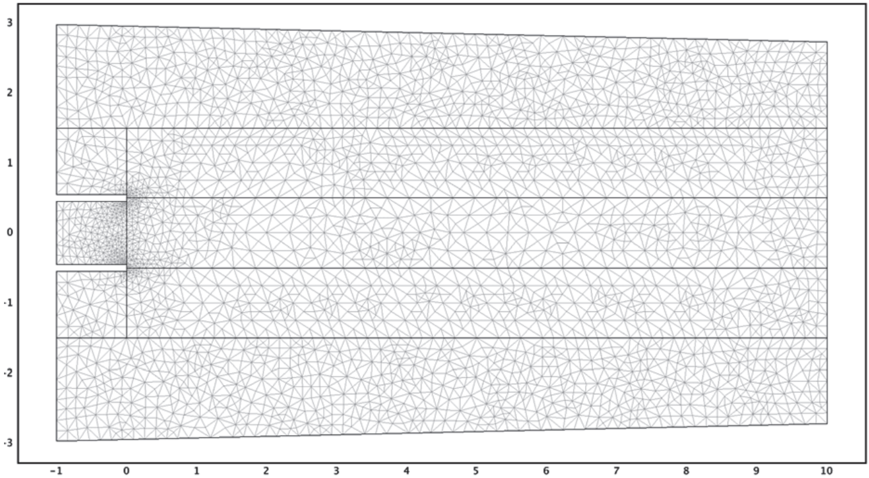


Figure 2 Geometry of the flow and the mesh used in the calculations.

Where U_{Aq} is the mean velocity in the vane and U_∞ the free-stream velocity in the headbox.

This type of flow (jet-wake problems) are difficult solve since they, as mentioned previously, by nature are inherently unstable. In addition, the instability that occur is not convective (i.e. the disturbances that appear are not convected downstream in time) but globally unstable. This implies that disturbances can be transported upstream and set up a self-sustained oscillatory motion. Thus the downstream condition is extremely important since it will give rise to a flow disturbance that can affect the solution in the whole domain. The usual way to treat this is to extend the domain far downstream. In addition, this means that it is impossible to find stationary solutions to the problem. As a result the flow has been solved as a time-dependent problem.

Numerical results

In Figure 3 the numerical result for the case of an Aq-vane with no flow is shown. The figure shows the velocity field (i.e. the magnitude of the local velocities) as a colour coded image. In addition, the velocity vectors (magnitude and direction) for a number of points are indicated with arrows. Clearly the blunt Aq-vane leads to a fluctuating flow very similar to the classical von Kármán vortex street. This implies severe mixing between the layers.

In Figure 4 the flow in the Aq-vane has been turned on and S_u=0.25. The

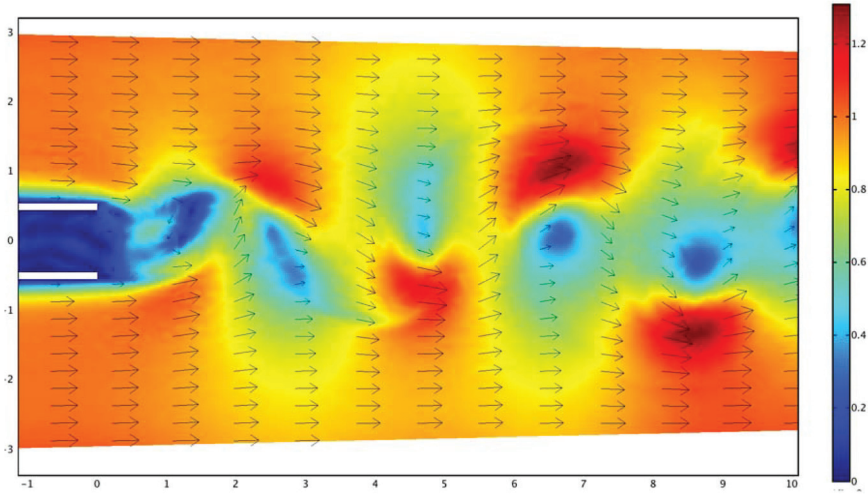


Figure 3 A numerical result representing the flow from the Aq-vane for the case S_u=0 at one specific time. In the graph the local magnitude of the velocity is colour coded. The velocity is also indicated with the arrows that indicate local speed and magnitude.

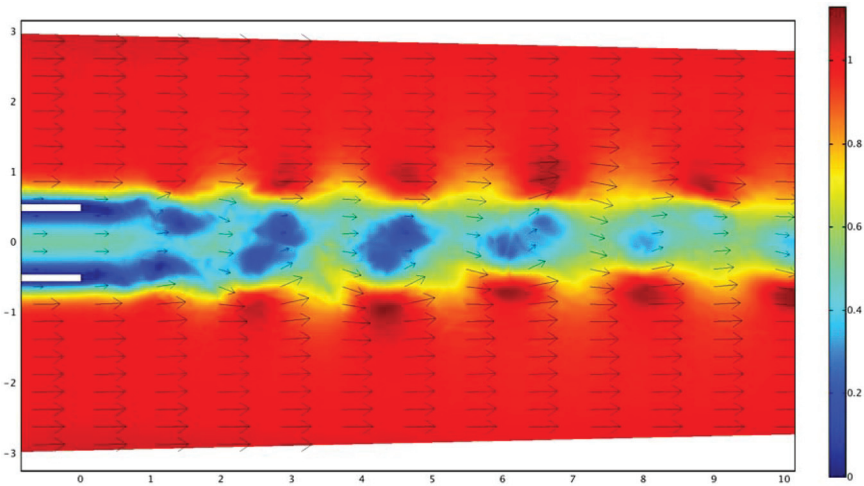


Figure 4 A numerical result representing the flow from the Aq-vane for the case S_u=0.25 at one specific time. In the graph the local magnitude of the velocity is colour coded. The velocity is also indicated with the arrows that indicate local speed and magnitude.

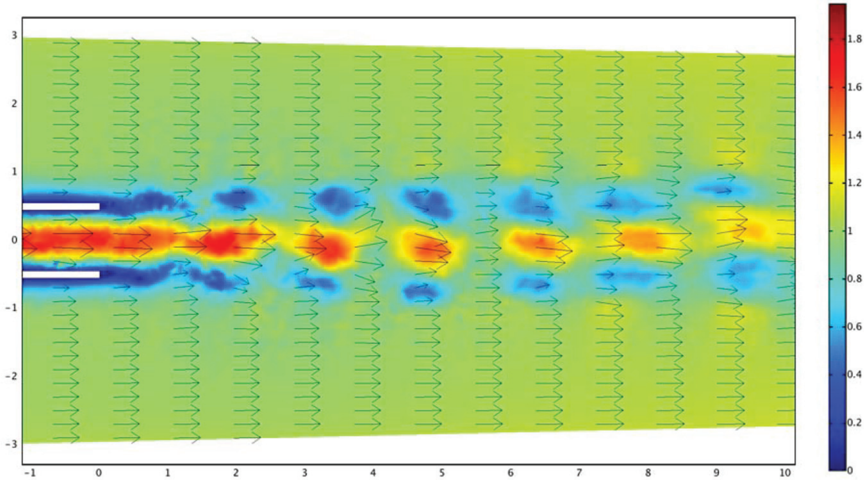


Figure 5 A numerical result representing the flow from the Aq-vane for the case S_u=1.0 at one specific time. In the graph the local magnitude of the velocity is colour coded. The velocity is also indicated with the arrows that indicate local speed and magnitude.

result is that the large-scale mixing has disappeared and been replaced by the vortex streets. These are in principle counter rotating, which means that the centreline of the Aq-vane acts as a symmetry line for the *u*-velocity. This means that the *v*-velocity is zero at this line. Hence there is no transport of fluid across this line.

When S_u=1.0, Figure 5, the flow from the Aq-vane is clearly expanding but the vortex street is very coherent.

Headbox visualisations

Experimental set-up

The free jet experiments have been performed using the same headbox as in the pilot-scale trials. In order to have visual access to the liquid jet the headbox was mounted outside the experimental paper machine on a rigid stand.

The visualisations were performed with a High-speed colour CCD camera (Phantom V5.1), which can capture time sequences at full resolution (1024×1024 pixels) at up to 1200 frames/s. It was mounted in two different positions, which can be seen in Figure 6. The first position was directly above the jet with strong flood light mounted directly under the headbox. The

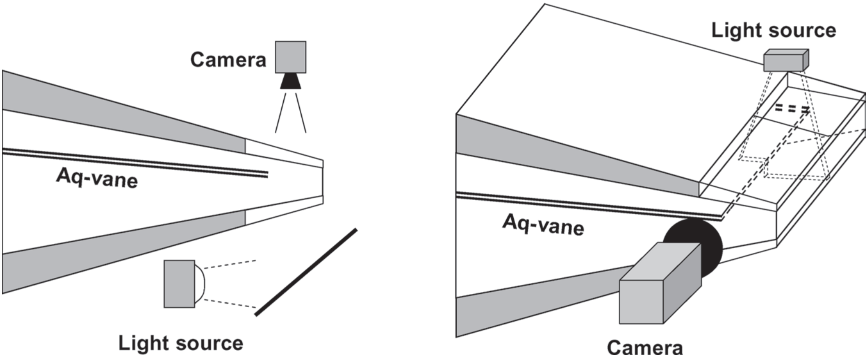


Figure 6 Schematic of the free-jet experiments performed. The set-up for visualisation of the vane tip in the MD/CD-plane (**left**) and for the visualisations of the MD/ZD-plane (**right**).

transmitted light is then recorded by the camera. The flow out from the Aq-vane was seeded with GCC filler and ideally this would provide a method for measurements of filler concentration variations in the MD/CD-plane.

In the second position the flow out from the Aq-vane is visualized using a light-sheet. The camera is then mounted at the side of the headbox, which results in an image of the MD/ZD-plane. This means that the mixing at the exit from the Aq-vane can be studied.

Experimental results

In Figure 7 the results from the visualisations can be seen. In the figure the outflow rates are shown, S_u=0.2, 1.0 and 1.5. The tips of the Aq-vane can be seen to the left in the images and the GCC addition to the liquid layer is clearly seen in the images. In the top image the tips of the Aq-vane are indicated.

At the lowest velocity of the liquid layer the mixing regions at the outer boundaries of the outflow from the Aq-vane is very well defined. They consist of two separate vortex streets. Also, the filler region is, in principle, contracting at all positions downstream of the tip.

For the case $S_u = 1.0$ there are no well defined visible vortices but a waviness can be clearly seen at the edges of the jet. Initially the jet is also expanding slightly but at the far right of the image a contraction of the jet can be seen.

For the last case shown, $S_u = 1.6$, there seems to be no structures in the jet at all and it is in principle only expanding.

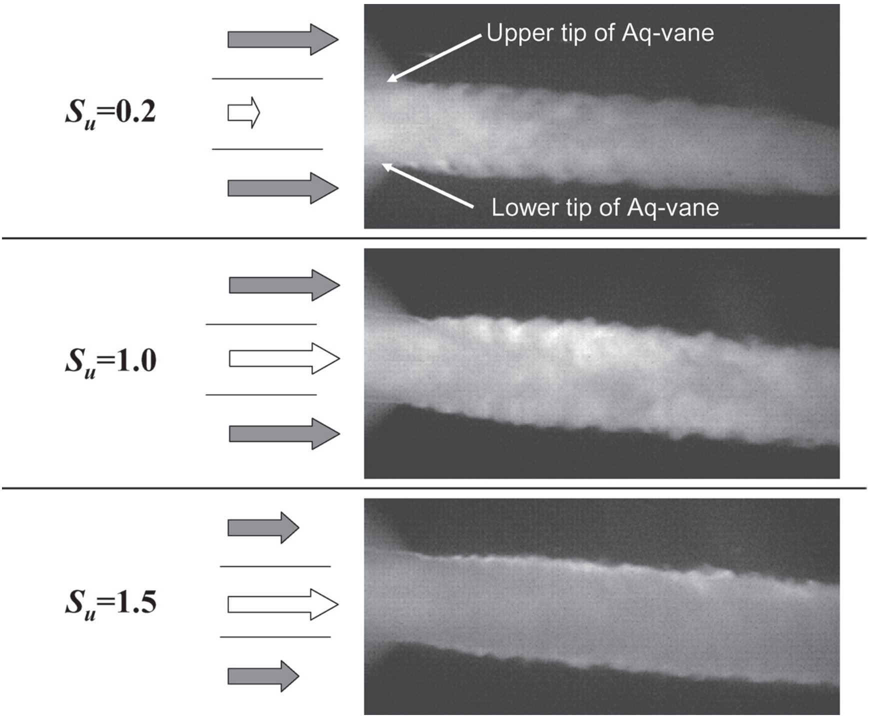


Figure 7 Results from the free-jet experiments. Visualisation of the flow after the Aq-vane where the flow speed in the liquid layer is varying.

It should be noted that for the cases shown here the Reynolds number for the flow inside the Aq-vanes is in the range 2.200–5.000, which implies turbulence. This can also be seen if the core of the jet leaving the Aq-vane is examined. The structure seems to be rough and hence turbulent. However, the flow on the outside of the Aq-vane is laminar, which is clearly seen for the case of $S_u = 0.2$. The well-defined vortex structure can only be a result of a two-dimensional laminar flow, which is even more obvious in Figure 8.

This figure shows the MD/CD-plane starting at the tip of the Aq-vane. The original image is more difficult to identify structures but using a long series of images the average can be identified. By subtracting this average from one singe image the variation can be enhanced. From this image the waves (CD-aligned vortices) can be clearly identified.

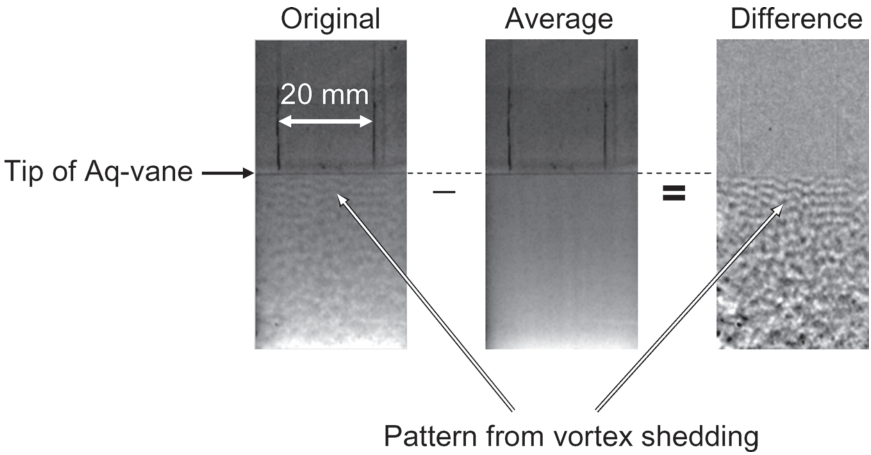


Figure 8 Results from the free-jet experiments. One single image with size indicated (**left**). By averaging a series of images a mean image can be obtained (**middle**). By subtracting the mean from the single image the variations are pronounced (**right**).

PILOT-SCALE EVALUATION

Layer mixing has been studied through free jet experiments and pilot-scale trials on the research paper machine (i.e. the FEX-machine) at STFI-Packforsk, Stockholm. All pilot-scale research discussed in this paper was performed with the forming set-up in Figure 9. Here the geometry of forming is simplified by the use of a solid forming roll, which results in single-sided dewatering towards the outer forming wire.

The experiments were performed using four different headbox configurations, see Figure 10. In the figure, these the different cases studied where the positions of the vanes are indicated. For two of the cases, A_{242} and A_{323}, both vanes are Aq-vanes. For the reference case (Ref_{242}) only traditional vanes are used and for case, B_{242} only the vane separating the blue from red is an Aq-vane. The subscript indicates the number of tubes in the tube bank for the different pulp streams. The open area of the vanes was approximately 20% of the local height of the headbox nozzle. This means that the Aq-vanes are thicker further away from the slice opening.

The pulp consisted of a 50/50 mixture of bleached softwood/hardwood (SR25°). In addition, the speed was always 600 m/min with 12 mm slice opening. If not explicitly stated all samples represent the case of zero jet-wire speed difference. This was determined by finding the minimum, which was determined, by finding the minimum TSO value.

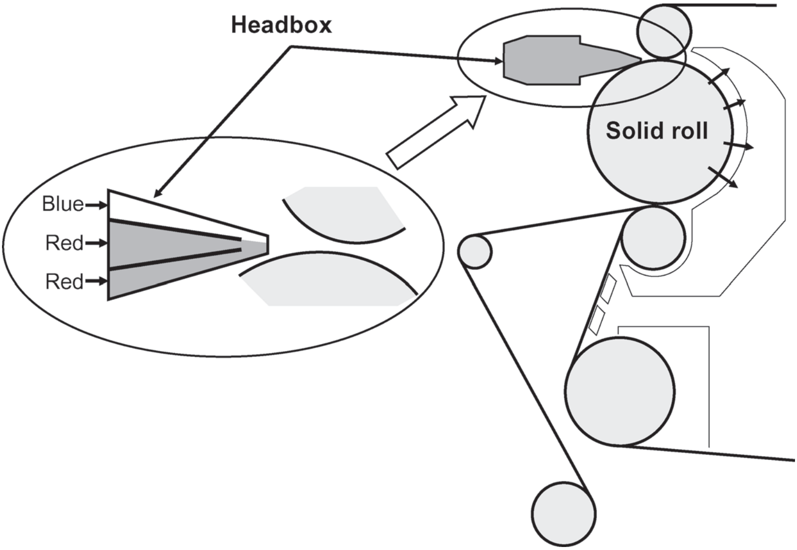


Figure 9 The detail of the headbox shows the set-up for a specific case with the blue layer positioned towards the outer wire and two red layers towards the solid roll. The experiments are performed in a roll-forming unit where the forming roll is solid. This implies that the dewatering is single-sided.

During the trials, the basis weight was kept constant 60 g/m^2 except for a slight variation when the jet-wire speed difference was deviating from zero. For all trial points the surface layer represented 20 g/m^2. Since only two feeds to the headbox are available this means that the red centre and surface layers together represented 40 g/m^2 with both layers having the same concentration.

Since the production and slice opening is constant, this means that the concentrations in the different layers are depending on the configuration and the amount of water used in the Aq-vanes. The different settings are summarized in Table 1.

Table 1 The concentrations in the different layers for different cases.

	Blue layer [g/l]	*Red layers [g/l]*
A_{242}	8.2	5.8
A_{323}	5.4	6.7
Ref_{242}	5.7	4.9
B_{323}	5.4	5.5

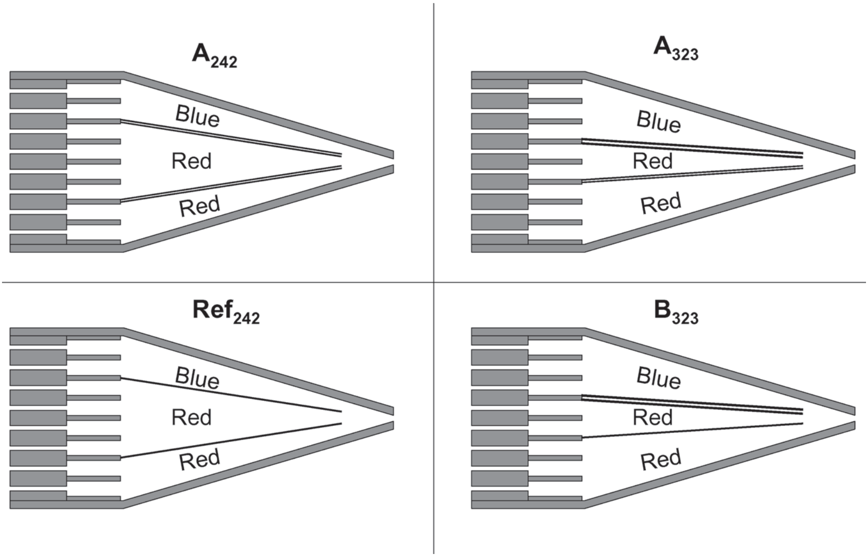


Figure 10 Schematics of the different cases studied where the positions of the vanes are indicated. For cases A_{242} and A_{323} both vanes are Aq-vanes. For the reference case (Ref_{242}) only traditional vanes are used and for case B_{242} only the vane separating the blue from red is an Aq-vane. The subscript indicates the number of tubes in the tube bank for the different pulp streams.

Layer purity evaluation

In order to quantitatively study layer purity there is and absolute necessity of an objective tool. This was made clear through initial investigations, which showed that the correct classification of samples of different layer purity is a complex task for a non-expert human observer.

The approach we adopted during our pilot scale trials was to dye the centre layer and the layer closest to the (solid) forming roll with a red dye, whereas the outer layer was dyed in blue. As can be seen in the figure the dewatering of the red coloured pulp is then performed through the blue "top-layer", which means that it represents the "worst case". Simple laboratory experiments were used to verify that the dyes had no significant impact on furnish flocculation and sedimentation properties, at least not at the concentrations used in the experiments.

The paper samples obtained in the experiments have been evaluated by studying the stratification profile, which is defined as the relative frequency of (blue) fibres destined to the surface layer of the sheet and its evolution in the thickness direction of the sample. In order to perform this analysis a quick and reliable technique for parallel splitting of paper into thin layers was needed.

The literature reports a number of methods for parallel splitting of paper; among them heat-seal pouch lamination is one of least known, although possibly the most effective. This technique, mentioned by Danby in several occasions (e.g. Danby, 2001 [25] and Danby and Zhou, 2003 [26]), has been discussed in some details in Knotzer (2000) [27] and Knotzer et al. (2003) [28]. According to this method, a paper sample is sandwiched between two laminated sheets, composed of a melting glue layer (e.g. EVA – Ethylene Vinyl Acetate) on a support layer of PET (Poly Ethylene Terephtalate). When heat and pressure are applied in a commercially available laminator, the adhesive softens allowing the plastic to adhere to and encase the paper. The laminator is composed of a pair of heated, rubber-covered rollers, a pair of stationary heated bars, a second set of (cold) rollers and a control system for setting temperature and lamination velocity, Figure 11.

After lamination the sample is split with a pair of counter-rotating splitting rollers. The operation of lamination and splitting can then be repeated for an arbitrary number of times, until the desired number of splits is obtained. Typically, a 60 g/m2 paper sheet can be split into 10 layers.

After splitting, all layers are relaminated for protection of the fibre material and stability. A flatbed scanner is used to acquire digital images of both faces of the splits whereby the relative frequency of blue pixels is

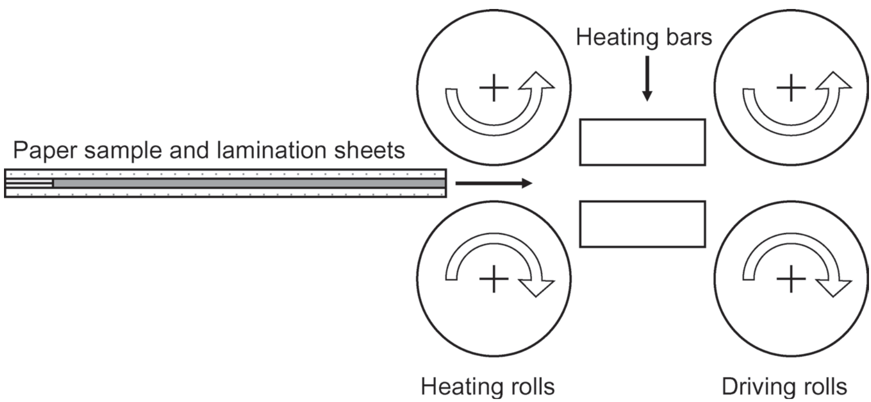


Figure 11 Lamination of a paper sample in a commercial hot laminator.

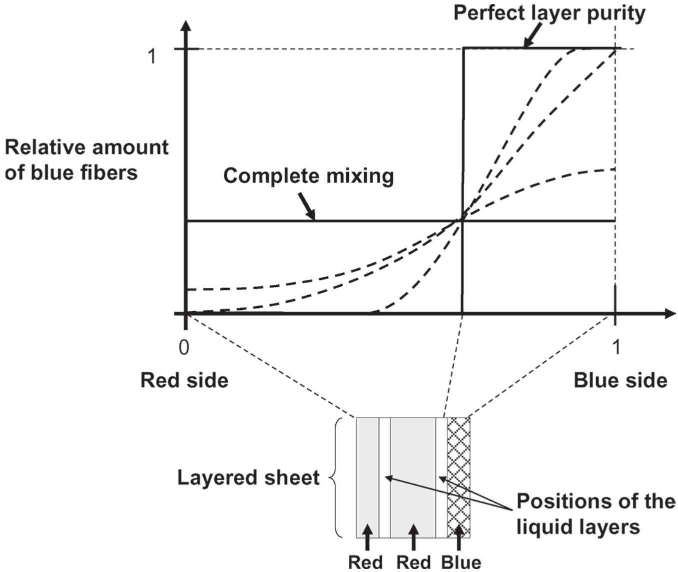


Figure 12 Schematic layer purity profiles evaluated by sheet splitting and image analysis. The graph shows the relative amount of blue fibres (pixels) in the scanned images of the split layers. The graph illustrates the ideal cases of perfect layer purity and complete mixing.

calculated in each layer using the image analysis algorithm developed by Sannes Lande (2004) [29].

Figure 12 gives a schematic illustration of the shapes of the measured stratification profiles: the horizontal axis gives the position in the thickness of the sample, whereas the vertical axis reports the relative fraction of blue fibres (furnish for the surface layers). All possible stratification profiles are included between the line for complete mixing and the step-function shaped line for perfect layer purity. Thereby, the objective of our research activities is to produce paper with stratification profile as close as possible to the line for perfect layer purity.

RESULTS

We have investigated the effect of both constructive and process parameters, generating a detailed matrix of experimental conditions. Our pilot machine studies show that some parameters have major effects on the stratification profile.

In Figure 13, the effect on layer purity of a difference in mean flow velocity between the passive water layer and furnish containing layers, calculated at the tip of the Aq-vane. In this figure Aq-vanes with two different lengths are shown. We termed "Short" the Aq-vanes ending at a distance of 150 mm from the slice opening and "long" those that end 50 mm from the slice opening.

Clearly, the speed of the water layer alone can result in the significant difference between rather well stratified structures and relevant interlayer mixing. From the left graph in the figure, it is obvious that we can reach a "pure" surface layer. For the case of a slight over-speed of the water layer the profile has an inflection point, i.e. it has a *S*-shape. However, this is not the case for the longer vane although almost the same layer purity is reached. It should be noted that the speed of the water layer in the long Aq-vanes does not exceed one. Since the vane ends closer to the slice, the speed is significantly higher at the vane tip compared to the short vane. In order to achieve the necessary speed the pump supplying the vanes has to generate a higher pressure (pressure is quadratic to the speed!).

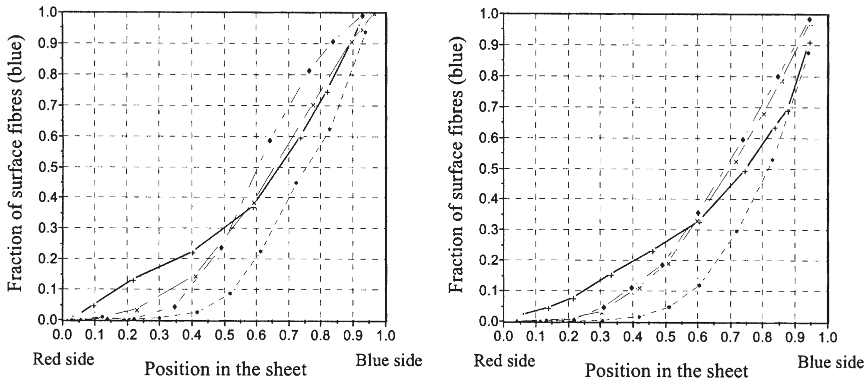


Figure 13 Effect of the difference in linear velocity between the passive water layer and the furnish flow, calculated through the volumetric flow at the tip of the Aq-vane. Stratification profiles for the case B_{323}. For the **left graph (short vanes)** the relative speed in the Aq-vane at the tip: 0.44 (solid), 0.70 (dashed), 1.02 (dotted), 1.24 (dash-dotted). For the **right graph (long vanes)** the relative speed in the Aq-vane at the tip: 0.33 (solid), 0.55 (dashed), 0.79 (dotted), 0.33 (dash-dotted)

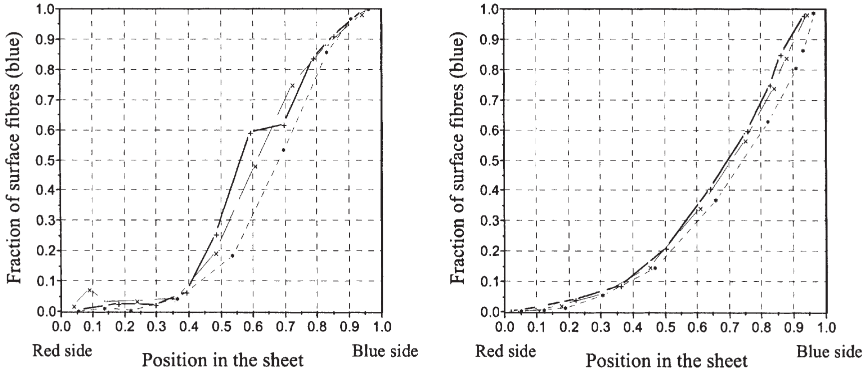
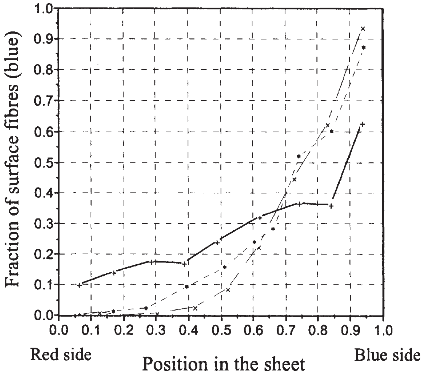


Figure 14 Effect of the jet-wire speed difference. Stratification profiles for the case B_{323}. The velocity between the passive water layer and the furnish flow; calculated through the volumetric flow at the tip of the Aq-vane is 0. For both graphs **(left-short vanes and right-long vanes)** the speed difference: 40 m/min (solid), 0 m/min (dashed) and –40 m/min (dotted).

In Figure 14, the effect of jet-wire speed difference in layer purity is plotted for the same case (B_{323}). For both long and short Aq-vanes, the speed at the tip of the vane is the same as the speed of the surrounding furnish. Clearly, the inflectional profiles are present only for the shorter vanes. There seems to be a slightly stronger effect of the jet-wire speed difference for the shorter vanes. Hence, the jet impact seems to have weaker effect on layer mixing compared to the speed of the water layer.

In Figure 15, a comparison between the different headbox configurations can be found. For the purpose of a fair comparison of the two technologies, we have followed the recommendations of Lloyd (1997) [12] for the set-up of conventional separation vanes (Ref_{323}). Clearly, the configuration has an effect. For the short vanes the case B_{323} gives severe mixing compared to the "symmetric" configurations. It should also be noted that there is no reference with conventional vanes for this vane-length.

For the longer vanes, the effect of configuration is only obvious for the conventional vanes. In addition, for this vane-length B_{323} case gives best result, which is the opposite of the shorter vanes.



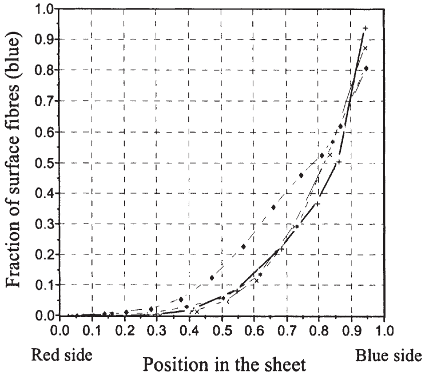


Figure 15 Stratification profiles for short and long Aq-vanes (**left** and **right** respectively). Effect of headbox configuration. The velocity between the passive water layer and the furnish flow; calculated through the volumetric flow at the tip of the Aq-vane is 0. For both graphs the speed difference: B_{323} (solid), A_{323} m/min (dashed), A_{242} (dotted) and Ref_{323} (dash-dotted).

Effect on formation and z-strengths

Since paper was produced during the trials, it was possible to compare physical properties. From these there were no clear effects of the Aq-vane technique on strengths and formation. Specifically, the formation (STFI β-formation) was not degraded and there were no results that showed that the additional water layer had a negative effect on z-strengths.

CONCLUSIONS AND DISCUSSION

This study describes the first application examples of the Aq-vanes technology for stratified forming where a thin passive liquid layer is injected in the headbox between neighbouring layers of different composition.

The numerical calculations and the lab-scale experiments confirm the fundamental idea of controlling the mixing hydrodynamically using a passive liquid layer. The pilot scale trials show that the layer purity is closely connected to the operational parameters of the Aq-vanes. This is a positive result since it makes it possible to control the degree of stratification for a machine operator by the on-line tuning of appropriate process parameters.

We have compared the stratification obtained with the Aq-vanes with that of a conventional separation vane installed in the same headbox and run with

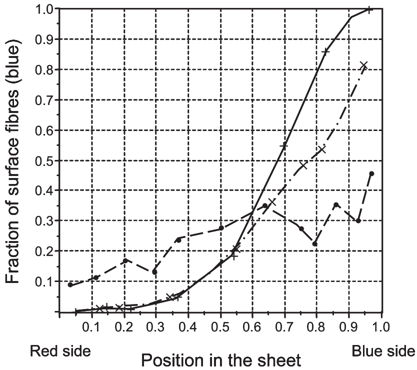


Figure 16 Comparison between the Aq-vanes technology (solid) and conventional separation vanes (dash-dotted) installed in the same headbox. The "worst result" (dashed) is given by a sample with high degree of layer mixing, produced with the Aq-vanes technology where the flow of the liquid layer has been turned off.

the same machine settings. For the purpose of a fair comparison of the two technologies, we have followed (as mentioned above) the recommendations of Lloyd (1997) [12] for the set-up of conventional separation vanes. Figure 16 shows the best stratification profile obtained in these trials with the Aq-vane technology, as well as the best results obtained with conventional vanes. Additionally, in the graph the profile with worst separation obtained during our experiments with the Aq-vanes is presented. The comparison between the best and worst result obtained with the Aq-vanes is an indication of one of the main process-related advantages of the Aq-vanes, namely its nature of being controllable through the tuning of process settings.

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Transcription of Discussion

REDUCTION OF LAYER MIXING IN STRATIFIED FORMING THROUGH HYDRODYNAMIC CONTROL

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Thad Maloney KCL

Two of the issues that one sometimes has with multilayer forming are streakiness and formation problems. Could you comment on your new technology in this respect?

Daniel Söderberg

Yes, I can. One thing, which I have not mentioned is that all the pilot scale trials, in contrast to the conventional design, are done at constant total concentration. This means that when you add the water layer, you increase concentration of the other layers, because you do not want to add more water in your process. The other thing is that there are good results available in the literature showing that 3-layered forming can improve formation in the different layers. I would say that one of the biggest tasks today for us in the development project is actually to get good enough formation on the top layers and no streakiness. Streakiness is a lesser problem generally, than formation and I think it is very much coupled to the quality of the headbox jet.

Hannu Paulapuro Helsinki University of Technology

Paper needs to be a compromise between many important properties depending on the end use. When you reduce mixing, what happens to the z-directional bond strength which is important for offset papers, for example?

Daniel Söderberg

We tested that in the pilot scale trials and as it turns out, as long as you only have water in between the layers, you do not lose strength. I think as soon as you start to put air in between the layers, you start to lose strength, which is done typically for board making. We have tested all our points with respect to z strength and I have not seen any effect at all. Of course, in the really mixed cases, it is not too difficult to believe, but then even in the best results, there is no effect on layer purity or layer strength I would say.

Hannu Lepomäki Metso Paper Inc

While the development of this most interesting new technology and the platform goes on, what do you think will be the first applications at the industrial scale? Will they be board machines or do you see opportunities to go directly to printing grades?

Daniel Söderberg

I would say that, if you look at the industry we talked to when we started the project and those participating, the strongest interest is, and the quickest interest is from the board makers, because I think they tend to have genes that think functionality.

I think that the first installation would probably be either as a high quality printing paper or possibly some board product where you actually do not make your board in one headbox, but what you do is actually improve the functionality of the top layer. The application of this, if this works, is not really only stratification, but you could couple it to fractionation, I think that would be the real killer application and that would be for printing papers primarily.

William Sampson University of Manchester

You made about ten sheet splits which gives us about 6 $g\ m^{-2}$ for the layers that you have done your analysis on. If the top surface fibres are approaching 100% blue, say, in the layer underneath you would still see some of the fibres underneath. So when you look at what should be just a blue surface, is it blue or is it purple?

Daniel Söderberg

It is never purple, because you are not mixing the colours. It is red and blue, but you have pinpointed the problem with formation. If we succeed and if you run it with good formation, you have no problem, but if you have bad formation, you can still get 100% layer purity and still see the red beneath. So, that is why I said that the major task is to keep a good formation.

Bob Pelton McMaster University

Very interesting presentation. I have been sitting here for 3 hours and I am pleased someone finally mentioned polymers, so what happened when you added polymers, you must have played with this a little bit?

Daniel Söderberg

We have played a little bit with it but what I can say today is restricted, since it is performed within the ongoing development project. You can improve the control of the effects by adding polymers.

Theo van de Ven McGill University

I guess I have a similar question to the previous one. If you add polymers or fillers or other additives through the vane, I guess then you would like some mixing, while if you require good formation, you want to avoid mixing. So, can you comment about these opposite effects?

Daniel Söderberg

I think I do not have the perfect answer to this. When you are looking at this effect, the mixing does not really affect formation. What you can do if you want to control the mixing is to control the speed. It may be that you do not want to run with exactly perfect layer purity, and if you add a little speed, you increase mixing in the narrow region closest to the water layer. What is coming out of this aquavane is clearly turbulent. So there is the possibility of modifying the geometry of the inside of the vane to control the amount of mixing you have.

Gary Baum PaperFuture Technologies

This is a practical question. What issues might there be in handling these hollow vanes in a commercial operation?

Daniel Söderberg

Plugging of them is the biggest issue.

Since this is a pilot machine and people perform a lot of different trials, I think that we are the ones that filter the system with the aquavanes. What you can do is to put a suitably chosen screen before the headbox in order to keep it clean.

Gary Baum

So filtering might be a requirement in a commercial installation?

Daniel Söderberg

Yes, possibly.

Gary Baum

This is a related question: what is the maximum width of machine you have looked at? Was your pilot machine the EuroFEX machine?

Daniel Söderberg

With the setup we have used here, I think that there is no maximum width. I think that, in the end, this is something for the machine suppliers to solve if the proposed concept is successful. What I would do in their shoes is to develop the industrial technology.

Roger Gaudreault Cascades Canada Inc

I want to make sure I clearly understand. You have mentioned that the mixing of layers does not change the z-directional strength. When we produce, for example, a 300 $g\ m^{-2}$ multi-ply board, it is clear in our mind that we need some mixing of the fibres (layers) to make sure that we get a good plybond strength.

Daniel Söderberg

Do you run stratified forming or a multi-ply forming?

Roger Gaudreault

Multi-ply forming.

Daniel Söderberg

And what I said was that when you do multi-ply forming, you actually put something on top of something else with air in between. I think this is very different from what we propose, where you never have air present which can affect your fibre-fibre bonding.

Roger Gaudreault

We have observed the loss of plybond strength when the mixing of the layers of a multi-ply board is insufficient.

Ari Kiviranta

I will briefly continue that point. If you consider that, instead of adding water between the layers, you could put some starch in there for instance, you may get better plybond. That is an attractive possibility. What was shown here were the result of trials with fillers and I guess that is something you do not want to do because then you completely lose the plybond.

Jean-Claude Roux EFPG-INPG

Very interesting paper. I was wondering what would happen if we put aquavanes in the z-direction and if we put a dilution controlled headbox in the cross direction. Have you done any experiments with the two together?

Daniel Söderberg

No. One possibility that we have thought about was of course to do some profiling utilising the aquavanes. The EuroFEX machine is a pilot machine and is not really wide enough to do CD control experiments.

Ari Kiviranta

Let us consider layer purity. It has already been discussed a little bit, but this is one of the most important points here in my opinion. The layer purity on the surface is 95%, and it might be improved to 97%, but if you have some structures in the x-y plane, that might be difficult to achieve. What is the absolute minimum basis weight for the surface layer?

Daniel Söderberg

I think it was the same question as asked by Bill Sampson.

Ari Kiviranta

More or less. This is a very critical point.

Daniel Söderberg

I guess that is one problem, but the biggest problem of all, if everything else would succeed, is to solve the process layout to handle white water, broke and so on.