HYDRODYNAMIC EFFECTS IN THE HEADBOX ON FIBER ORIENTATION AND FORMATION: PART I

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January 1995
EXECUTIVE'S SUMMARY

The objectives of this project are to enhance the quality and the productivity of the paper and board produced by the CKPG member companies by analysis and optimization of the headbox and the forming section, in general. Important physical properties of paper and board depend primarily on the flow characteristics inside the headbox. This project is part of a comprehensive research program to investigate the hydrodynamics of the forming section and its effects on the physical properties in terms of uniformity of mass formation, fiber orientation, freeness, strength, twist-warp, crush strength, etc.

The success of this project is measured by the effectiveness of the methods developed in this project to analyze and optimize the headboxes of the CKPG member companies with direct improvements in quality and production. We have completed a project with a CKPG member company, which has resulted in eliminating their fiber orientation problems even at low rush/drag ratios. We have started a project with a second CKPG member company to analyze and optimize their headbox for superior performance. Projects with two other CKPG member companies will start in 1995.

During the first phase of the project, the focus has been on diagnostics and identification of the physical origin of nonuniformities in the headbox and the forming section. The first phase of the project has been completed and a complete report on Phase I will be distributed at the January 1995 meeting of the Technical Committee. As continuation of this project, we are starting Phase II where a mechanism for systematic optimization of the headbox for best performance will be established by analyzing and optimizing the flow characteristics in the distributor and the tube bank.

The results from Phase I of this project have produced several definite conclusions which have been confirmed in practice. A critical comparison of the cases with no side ejection shows a consistent behavior - the geometry has a significant effect on cross-flow and pressure variations inside the headbox. The nonuniformity in the slice profile, however, has a more significant effect on cross-flow. Comparing the cross-flow for the three cases of 1.5" uniform slice, 1.25" uniform slice, and the 1.35"-1.39" nonuniform slice, considered in Phase I of this project, it becomes clear that as the slice opening decreases from 1.5" to 1.25", the cross-flow increases significantly. For the case with nonuniform slice (1.35"-1.39"), however, the cross-flow is even greater than the 1.25" uniform slice, although the slice opening is larger. To summarize, we
make the following specific conclusions about the effects of the headbox variables on cross-flow at the slice and, consequently, nonuniformity of fiber orientation:

1. Even in a headbox that is perfectly uniform and has perfect uniform influx in CD, the retardation of the flow at the side walls alone will generate cross flows at the slice.

2. The cross flows at the slice result in nonuniform fiber orientation and mass formation.

3. Cross flows and nonuniformity in fiber orientation increase by increasing the side ejection flow rate at the 'checkin piece bleed valves'.

4. Cross flows and nonuniformity in fiber orientation increase by decreasing the slice opening.

5. Cross flows and nonuniformity in fiber orientation increase more significantly with nonuniformity of the slice profile.

6. The most effective way of removing the cross flow caused by the flow retardation at the side wall is to optimize the influx in order to compensate for the flow deficit and to cancel the side wall effects on the flow.

7. The most effective way to optimize the influx is to optimize the insert tube arrangement and size.

8. Influx variations in the Z-direction should be avoided.

9. The vanes (converflo elements) result in additional turbulent kinetic energy which would enhance formation. Adding the converflo elements to the headbox slightly reduces the streamwise velocity and, therefore, the cross flow and nonuniformity in fiber orientation. Once the influx is optimized to eliminate cross flow, then the converflo elements will have no effect in terms of CD nonuniformity.

These results show that geometry, headbox size, slice profile and shape, and flow rate are all important parameters which need to be considered together in the analysis in order to reliably and accurately evaluate and optimize a headbox. The optimization method used with this approach has been implemented on a member company's headbox which has effectively eliminated their fiber orientation problems. The consistent results from this project and the
complementary projects with member companies have verified the effectiveness of our approach in resolving nonuniform fiber orientations problems.

The research program on the Hydrodynamics of Paper and Board Forming is being funded in part by the National Science Foundation (NSF), the Containerboard and Kraft Paper Group (CKPG) of AFPA, and individual member companies. The fundamental methods that are used in this project are developed by funding from NSF and the application of these methods to commercial scale headboxes are through the CKPG project.

1. OBJECTIVES AND TASKS COMPLETED

The overall objectives of this project are to demonstrate the effect of various headbox operational parameters on fiber orientation. The specific tasks are to:

(a) analyze the hydrodynamic characteristics of the headbox with uniform pressure distribution at the tube bank,

(b) determine the effects of 'stick-down' on cross-flow at the slice,

(c) determine the effects of nonuniform flow distribution at the header/tube bank on cross-flow,

(d) compute the significance of nonuniform slice opening on generation of cross-flow,

(e) analyze the effects of side ejection on fiber orientation,

(f) investigate the structure of secondary flows inside the headbox,

(g) investigate the effects of vanes on the hydrodynamics inside the headbox.

2. PROJECT TIME TABLE

<table>
<thead>
<tr>
<th>Tasks</th>
<th>Time</th>
</tr>
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<tbody>
<tr>
<td>a</td>
<td>June 1993</td>
</tr>
<tr>
<td>b</td>
<td>Sept.</td>
</tr>
<tr>
<td>c</td>
<td>Dec.</td>
</tr>
</tbody>
</table>
3. DIRECT APPLICATION OF RESULTS BY THE INDUSTRY

The results from this project show the hydrodynamic characteristics and the effects of flow patterns in a specific headbox system on fiber orientation. The information can be used to:

(a) identify the specific features of the flow in the forming section that most significantly contribute to the undesirable fiber distribution and fiber orientation,

(b) adjust the flow parameters to improve product qualities such as twist-warp and crush strength,

(c) improve understanding of the headbox performance by the process engineers and the operators,

(d) improve design and modification of the headbox for superior formation,

(e) improve trouble shooting and analysis of a headbox at startup.

4. CRITERIA FOR INITIAL HEADBOX SELECTION

The flow patterns inside a headbox depend greatly on the geometry and the specific features of the headbox. Therefore, we have to focus our studies initially on a specific headbox. At a CKPG meeting, we established a set of criteria to select a headbox for this study. The list of criteria included the proximity to IPST, the degree of geometric complexity, grade, and other factors. We contacted several mills and based on the list of criteria, selected the Y1 headbox at a southern mill, X1, producing unbleached board. This mill has requested that for now we refer to them as the X1 mill.
5. SUMMARY OF RESULTS FOR 90 lb AND 42 lb GRADES

The specifications of the headbox (see Fig. 1 and 2 for a schematic), Y1, are listed below:

- Machine width: 325" 
- Total flow rate: 50,000 gal./min. 
- Maximum slice opening, B: 3" (90 lb) 
- Hangdown (stick-down), s: 0 to .08" 
- Slice opening, b: B - s 
- Bottom lip extension, L: 0 to 1" 
- No vanes, No side ejection

It is now well established that flow in the cross-machine direction results in fiber misalignment and disorientation. The particular orientation depends on the jet velocity relative to the wire speed (rush/drag condition). We are investigating the main cause of fiber disorientation, that is, cross-machine direction (CD) flow in the headbox.

![Fig. 1 Schematic of the Y1 Headbox.](image)

![Fig. 2 Schematic of an individual tube.](image)

The computational analyses are organized such as to establish the degree of importance of various parameters associated with a particular headbox on CD flow. In order to distinguish the effects of various parameters and flow conditions that could be adjusted in an actual operation, we start by introducing these parameters in a sequential manner. That is, we start with the most
ideal setting - constant CD pressure profile and flow distribution at the tube bank. We then demonstrate the effect of mass flux or pressure variation in the tube bank on cross-flow at the slice. The results presented below also include the effects of slice profile, side ejection, and the effect of 'stick-down' at the slice on nonuniform cross-flow in the headbox. In later sections we introduce and study the effects of other parameters (as listed in section 1) that are present in a real headbox.

The first set of results is obtained by full three-dimensional computational analyses of the flow inside the converging section of the Y1 headbox. The geometry and dimensions are exactly the same as the drawings provided by the mill personnel. The parameters are set for L=0 and s=0, 4% and 10% of B. We have computed the flow for several flow rates and slice openings representing a heavy grade (3” slice at 50,000 Brit. gal./min.) and a 42 lb grade (1.5” slice at 48,000 Brit. gal./min.).

Fig. 3 shows the exact geometry of the Y1 converging section and the slice. Because the pressure and flow rate distribution at the inlet (tube bank) and all other boundary conditions are symmetric with respect to the centerline, we consider half of the headbox and treat the left side as a symmetry plane. The results are summarized below.

Table 1 can be used to convert the dimensionless numbers in the figures to dimensional quantities.

<table>
<thead>
<tr>
<th>To convert dimensionless variable to</th>
<th>for the case of 50,000 gal./min or 3&quot; slice, multiply by</th>
<th>for the case of 48,000 gal./min. or 1.5&quot; slice, multiply by</th>
</tr>
</thead>
<tbody>
<tr>
<td>length</td>
<td>m (ft)</td>
<td>0.337 (1.1056)</td>
</tr>
<tr>
<td>velocity</td>
<td>m/s (ft/min.)</td>
<td>1.355 (266.73)</td>
</tr>
<tr>
<td>pressure</td>
<td>N/m² (psi)</td>
<td>1836 (0.2663)</td>
</tr>
</tbody>
</table>

First, we consider a uniform pressure at the inlet to the box. The resulting pressure contour lines in the symmetry plane are shown in Fig. 4. The contour plots show that, as expected, pressure decreases as the fluid is accelerated through the box. The pressure contour lines become denser near the outflow, indicating sharper decrease in pressure (larger pressure gradient) due to the rapid velocity increase toward the channel exit, as illustrated in the velocity vector plot in Fig. 5.
Figure 3. Computational grid system for the Y1 headbox. X, Y, and Z are the spatial coordinates of a cartesian frame of reference.
Figure 4. Pressure contour plot at the middle cross-section.
Figure 5. Velocity vector plot at the middle cross-section.
These plots only show a cross-section of the headbox. To learn more about the global feature of the flow, we need to examine the pressure variations in CD.

In order to examine the pressure distribution in the headbox, the gray-scaled (color-coded original available on request) pressure surface plots are shown in Fig. 6a. This figure shows a three-dimensional view of pressure on the boundaries of the headbox. Fig. 6b shows the pressure contours (isobars), designated by regions with the same color, in a horizontal plane located in the middle of the slice. Although the boundary conditions are uniform in CD, the isobars demonstrate that the variation in the pressure field is three dimensional. That is pressure changes in the cross machine direction as well as the machine direction.

For quantitative information, the magnitude of the pressure variation at various levels of the slice, presented in Fig. 6c, can be compared to the plot of the machine direction (MD) pressure drop in Fig. 6d. The pressure variation in CD is primarily due to the retardation of velocity near the sidewall. Our objective is to study the effects of flow on fiber orientation. Therefore, it is important to examine the effect of the CD pressure variation on the flow. In other words, does the CD pressure gradient generate finite cross-flow?

To address this question, we need to examine the y-component (or cross-machine, CD, component) of velocity, \( v \), inside the headbox. The computational results for the contour plots of \( v \), shown in Fig. 7, clearly indicate a local minimum near the sidewall. The value of this local minimum is relatively small compared to the positive value of the cross-flow velocity. This can also be seen by Fig. 7a which illustrates the distribution of the y-component of velocity in the slice.

The relative magnitude of the velocity components is the important factor in fiber orientation. More precisely, the ratio of the cross-flow velocity to MD component of velocity subtracted by the wire speed is the relevant ratio. That is,

\[
\text{relevant velocity factor} = \frac{v}{u - q}
\]
Pressure contour plot

Figure 6. (a) Pressure contour plot on the boundaries of the headbox, and (b) top view of the pressure contour plot at the horizontal plane intersecting the middle of the slice.
Figure 6. (c) CD pressure variation at the headbox, and (d) MD pressure drop.
Figure 7. Contour plot of the Y-component of fluid velocity in cross-machine direction inside the headbox. (a) at the slice, and (b) top-view of the horizontal plan on the boundaries of the headbox.
where $q$ is the machine speed, $u$ and $v$ are the MD (x) and CD (y) components of velocity, respectively.

Figs. 8 and 9 show the MD and CD components of velocity along a line in the middle of the slice, respectively. It is clear from these figures that in addition to the local minimum near the sidewall, there is also a positive cross-flow which reaches a maximum at about 3.3 ft (1 m) from the sidewall of the headbox. Comparing the x- and y-components of velocity, we can show that the maximum cross-flow is about 1% of the x-component of velocity. The cross-flow is generated due to the converging section of the headbox in the $x$-$z$ plane bounded by the vertical sidewalls. The vertical sidewall retards the flow in the streamwise direction, and thus, by mass conservation, the flow is forced to move in the CD.

These results show that even when a perfect pressure and flow rate distribution exist in the tube bank, the flow inside the Y1 headbox will be three-dimensional. Furthermore, the results show the location of the maximum cross-flow.

The formation and flocculation is in part controlled by the turbulent flow characteristics. We have computed and plotted the turbulent characteristics inside the headbox in Fig. 10, where Figures 10a, b, and c show three-dimensional views of the turbulent kinetic energy, $k$, dissipation, $\varepsilon$, and turbulent viscosity, $\mu_t$, in the headbox, respectively. These figures show a somewhat uniform turbulent intensity in the Y1 headbox. The only regions with somewhat large variations in turbulent kinetic energy, dissipation, and viscosity are near the solid walls of the converging channel. Here, as expected, there are large velocity gradients resulting in a more intensive turbulent energy production and dissipation.

6. MORE RESULTS FOR THE 42 lb GRADE

The remaining computations focus on a 42 lb grade which are produced by the Y1 headbox. The slice opening for this case is 1.5" and the flow rate is 48,000 Brit. gal./min. Fig. 11 shows the cross-sectional velocity vector plot for this case at the symmetry plane. The main issues studied in this section are the effects of the influx variation and the slice opening on the cross-flow at the slice. More results for this grade will be provided below.
Figure 8. The x-component (MD) of fluid velocity, \( u \), at the middle of the slice.

Figure 9. The y-component (CD) of the fluid velocity, \( v \), at the middle of the slice.
Figure 10. Three-dimensional view of
(a) Turbulent kinetic energy,
(b) turbulent dissipation rate, and
(c) turbulent(eddy) viscosity.
Figure 11. Velocity vector plot at the symmetry plane.
One of the issues is the degree of accuracy of the computational results. To examine this, we searched for experimental results which we could use to compare our calculations with.

We first compared the streamwise velocity obtained from our calculations with the parameters provided by the X1 mill. For the first set of calculations which apply to a maximum 3” slice and the highest basis weight board manufactured by mill X1, the average streamwise velocity at the slice is 1180 ft/min. or 4.43 dimensionless velocity units. Also mill X1 produces a 42 lb grade with the streamwise velocity of 2260 ft/min. or dimensionless velocity of 9.04. The comparison of the given average streamwise velocity and the predicted average velocity from the computations for both grades are given in Fig. 12. We should note that the computed results provide a local average which are more accurate than the given average value since the flux varies in CD due to the velocity retardation at the side wall. As the comparison shows, the results are very close.
6.1 The Influence of Nonuniform Flux on Cross-Flow at the Slice

The effect of nonuniform influx at the inlet to the headbox on the cross-flow at the slice is examined by dividing the inlet into three sections as shown in Fig. 13. The flux at region B is the average of the flux in regions A and C. Figure 14 shows the cross-flow at the slice when the flux in section C is ±2% and ±10% of the flux in region C. The results show that slightly increasing the flux near the sidewall would reduce the cross-flow while too much influx will cause negative cross-flow. This result is consistent with the physical explanation of the nonuniform CD velocity by the retardation of the flow due to the sidewall. The additional flow rate compensated for the retarded flow resulting in less cross-flow at the slice. However, too much influx near the sidewall acts in an opposite manner promoting cross-flow toward the symmetry plane.
In principle, with a more gradual distribution of the influx, one should be able to substantially reduce CD flow and fiber disorientation.

Figure 13. Schematic of regions showing variation in influx profile.

![Schematic of regions showing variation in influx profile.](image1)

Figure 14. Variation of the cross-machine direction velocity profile across the headbox.

![Variation of the cross-machine direction velocity profile across the headbox.](image2)

### 6.2 The Influence of a Flow Constraint (B-s) on Cross-Flow at the Slice

The effect of constraining the flow at the slice by a vertical plate, better known as a 'stick down' or 'hang-down' is examined in this section. The flow in the headbox for four additional cases are computed where the vertical plate restricts 4% and 10% of the slice for the case of the 3" (50,000 gal./min.) and 1.5" (48,000 gal./min.) slice. For each case, the effect of the slice constraint on the cross-flow at the slice is presented in Figures 15 and 16. In both cases, the decrease in slice opening (B-s) increases the magnitude of the CD velocity component. In fact, decreasing the slice opening, increases both components of velocity at the slice, that is, the streamwise and the
CD (Y) components. However, these variations are relatively small compared to the effects of the nonuniform influx.

**Figure 15.** Variation of the cross-stream velocity component at the slice (B=3") for complete slice opening, 96% slice opening, and 90% slice opening.

**Figure 16.** Variation of the cross-stream velocity component at the slice (B=1.5") for complete slice opening, 96% slice opening, and 90% slice opening.
7. CONFIRMATION OF THE METHOD

Through an externally funded project for a member company, we used our computational approach to evaluate the hydrodynamics of their headbox with the objective to optimize the influx to achieve a more uniform fiber orientation. The optimized influx profile was obtained computationally. The arrangement of the insert tubes was optimized to achieve the same influx profile found computationally. The insert tube profile on the headbox was adjusted accordingly during a machine down time. This simple modification eliminated the fiber orientation problem even at low rush/drag ratios. Consequently, the machine can now operate at low rush/drag ratio with improved uniformity in the MD/CD strength properties. This is a direct validation of our approach and a confirmation of this method's effectiveness in optimizing the hydrodynamics of the forming section.

8. HEADBOX PARAMETER VARIATIONS FOR 42 LB (48,000 U.S. GALLONS PER MINUTE) GRADE

Our focus in this section, is on the (1) side ejection through the valves placed at the side walls ('cheeking piece bleed'), (2) reduction of the slice opening 'stick-down', and (3) slice profile nonuniformity. Each one of these parameters influences the cross flow at the slice.

The results are presented as dimensionless numbers. Table 2 can be used to convert each quantity to dimensional values.

<table>
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<th>TABLE 2. Conversion factors for nondimensional to dimensional units</th>
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<tr>
<td>velocity</td>
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<tr>
<td>pressure</td>
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All of the results presented in this report are for a 42 lb board with 48,000 U.S. gallons per minute flow rate. The Reynolds number for this system is $Re = 366860$.

8.1 Effect of Side Ejection on the Cross Flow

The ejection valve is placed at the side wall close to the inlet of the headbox as shown in the computational grid system presented in Figure 17. This is a new grid system which is reconstructed to incorporate the flow through the side valves in the computations. The side ejection flow rates of 0, 50, 100, and 150 gpm are studied. The pressure drop in the machine direction at the side wall and the symmetry plane are shown in Figures 18a to 18d. As clearly shown in Figures 18c and 18d, there is a local pressure drop near the inlet at the side wall as the flow through the side valve increases.

The cross-machine velocity component is plotted for each case at various locations inside the headbox up to the slice (Figures 19a to 19d). The side flow at $x/L = 0.5$, where the side valve is located, can be clearly distinguished in plots 19b, 19c, and 19d. The magnitude, of course, increases with the side ejection flow rate to a maximum of 0.4 (85 fpm) as shown in 19d.

The cross flow increases by increasing the flow through the side valves because of the additional cross-machine pressure drop due to the side flow. This effect is shown in Figure 20, where the cross-machine velocity components of each case is shown in the same plot.

8.2 Effect of Slice Opening Reduction on the Cross Flow

To investigate the effect of reducing the slice opening, we have considered a case where the 1.5" slice is reduced to 1.25" by uniformly lowering the 'stick-down' plate by 0.25". Reducing the area at the slice where the fluid leaves the headbox must result in additional pressure buildup inside the headbox. This is shown in Figure 21a where the pressure profile along the mid-plane and the side wall are plotted. Comparing this result with the pressure for the 1.5" slice shown in Fig. 18a, one can see that the pressure inside the headbox considerably increases from about 45 (7.75 psi) to about 88 (15 psi) at the inlet. Furthermore, comparing the difference between the pressure profile at the side wall with the profile at the center of the headbox in Figures 21a and 18a, it is clear that reducing the slice opening increases the pressure gradient in CD. This would enhance the cross-flow in the headbox.

The cross flows, $v/U$, at different streamwise locations are plotted in Figure 21b for the 1.25" slice. Also, the variation of the cross flow from top to bottom of the slice is presented in 21c.
Figure 17. Computational grid system with the side ejection valves
Figure 18a. Pressure profile in the headbox along the machine direction at middle symmetry plane and at the side wall. (1.5" slice, 0 gpm side ejection)
Figure 18b. Pressure profile in the headbox along the machine direction at middle symmetry plane and at the side wall. (1.5" slice, 50 gpm side ejection)
Streamwise pressure distribution (1.5", 100gpm)

Figure 18c. Pressure profile in the headbox along the machine direction at middle symmetry plane and at the side wall. (1.5" slice, 100 gpm side ejection)
Figure 18d. Pressure profile in the headbox along the machine direction at middle symmetry plane and at the side wall. (1.5" slice, 150 gpm side ejection)
Cross flow, $v/U$, at different streamwise locations
(1.5", 0 gpm)

Figure 19a. CD component of velocity, $v/U$, from the tube bank to the slice for 1.5" slice with 0 gpm side ejection.
Figure 19b. CD component of velocity, \(v/U\), from the tube bank to the slice for 1.5" slice with 50 gpm side ejection.
Cross flow, \( v/U \), at different streamwise locations (1.5", 100 gpm)

Figure 19c. CD component of velocity, \( v/U \), from the tube bank to the slice for 1.5" slice with 100 gpm side ejection.
Cross flow, v/U, at different streamwise locations  
(1.5", 150 gpm)

Figure 19d. CD component of velocity, v/U, from the tube bank to the slice for 1.5" slice with 150 gpm side ejection.
Cross flow, v/U, in the middle of slice

Figure 20. Comparison of the CD component of velocity, v/U, for 0, 50, 100, and 150 gpm side ejection (1.5" slice opening).
Figure 21a. Pressure profile in the headbox along the machine direction at middle symmetry plane and at the side wall. (1.25" slice opening)
Cross flow, \( v/U \), at different streamwise locations

(1.25"(0.25"),0gpm)

Figure 21b. CD component of velocity (cross flow), \( v/U \), from the tube bank to the slice (1.25" slice opening).
Cross flow, $v/U$, at slice (1.25"(0.25"),0gpm)

Figure 21c. CD component of velocity (cross flow), $v/U$, along a uniform slice with 1.25" opening.
Vertical velocity, $w/U$, at slice (1.25"(0.25"),0gpm)

Figure 21d. Vertical component of velocity, $w/U$, along a uniform slice with 1.25" opening.
Streamwise pressure distribution (1.35"-1.39",0gpm)

Figure 22a. Pressure profile in the headbox along the machine direction at middle symmetry plane and at the side wall (nonuniform slice).
Cross flow, v/U, at different streamwise locations
(1.35"-1.39", 0gpm)

Figure 22b. CD component of velocity (cross flow), v/U, from tube bank to a nonuniform slice.
Cross flow, v/U, at slice (1.35"-1.39", 0gpm)

Figure 22c. CD component of velocity (cross flow), v/U, along a nonuniform slice.
Figure 22d. Vertical component of velocity, w/U, along a nonuniform slice.
Figure 23a. Pressure profile at the side wall of the headbox in machine direction for constant slice opening at 1.5", 1.25", and nonuniform slice profile, 1.35"-1.39".
Figure 23b. Pressure profile at the middle of the headbox in machine direction for constant slice opening at 1.5", 1.25", and nonuniform slice profile, 1.35"-1.39".
Cross flow, v/U, in the middle of slice

Figure 24. Cross flow profile for constant slice opening at 1.5", 1.25", and nonuniform slice profile, 1.35"-1.39".
along with the vertical component of velocity at the slice presented in 21d. These profile shapes are expected for turbulent flow. For example, the flat profile in 21c is a characteristic of high Reynolds number turbulent flow.

8.3 Effect of Nonuniform Slice Opening on the Cross Flow

The same sequence of information is presented in Figures 22a to 22d for a nonuniform slice profile. The slice on many headboxes are profiled such that the sides are slightly more open ('smiling slice'). We have adjusted the slice opening where it gradually varies from 1.35" in the major portion of the slice to 1.39" near the side walls. The variation is gradual (quadratic) and starts at 40 inches from the sides. From Figure 22a, it is clear that the pressure variation (gradient) in CD increases with this nonuniformity. This enhances cross flow as shown in Figure 22b and 22c. It also has some effect on the vertical component of velocity, as shown in Figure 22b.

A critical comparison of the cases with no side ejection shows a consistent behavior, the geometry has a significant effect on cross flow and pressure variations inside the headbox. The streamwise pressure profile at the side wall and the middle plane of the headbox, plotted in Figures 23a and 23b, respectively, show that pressure increases considerably as the slice opening is reduced. Furthermore, the variation in pressure (dp/dy) across the machine also increases by reducing the slice opening. This enhances cross flows at the slice.

The nonuniformity in the slice profile, however, has a more significant effect on cross flow. Let's compare the cross flow for the three cases of 1.5" uniform slice, 1.25" uniform slice, and the 1.35"-1.39" nonuniform slice, as presented in Figure 24. It is clear that as the slice opening decreases from 1.5" to 1.25", the cross flow increases substantially. For the nonuniform slice, however, the cross flow is even larger than the 1.25" case, although the slice opening is greater.

9. CONFIRMATION OF THE PHYSICAL MECHANISM FOR GENERATION OF SECONDARY FLOWS DUE TO THE SIDE EFFECT

Uniformity of the physical properties in the cross-machine direction (CD) is one of the most important properties in manufacturing paper and board. Nonuniformities in average fiber orientation and mass distribution, two of the most common quality problems, could be the result of: (1) imperfect setup of the forming section or (2) hydrodynamic effects. Examples of an imperfect setup are unbalanced pressure in the manifold or distributor, plugging of the tubes in
the tube bank, flow injection or ejection into and out of the headbox from the side walls, misalignment of the headbox with the wire, nonuniform slice profile, and nonuniform wire permeability (drainage properties). All of the effects from an imperfect setup will to some degree result in nonuniform properties in CD. The effects of these imperfections on the forming properties are relatively simple to understand and resolve. However, even if the setup of the forming section is perfect, there are purely hydrodynamic issues which may result in significant nonuniformities in paper and board formation properties.

The hydrodynamic effects could be in the form of flow instability, where a base flow becomes unstable and is replaced by another flow pattern with qualitatively different flow characteristics, or secondary flows where a weak flow pattern is superimposed on the primary flow. Although hydrodynamic instability is very important in papermaking processes, in this project we focus on the secondary flows and their effects on nonuniform CD properties.

In the previous reports, we demonstrated the effects of side walls on generating cross-flows inside the headbox. The flow component in CD results in misalignment of the forming jet with the wire near the side wall. Consequently, the fibers forming near the side wall experience shear in CD on the forming table and form with an average orientation different from the fiber orientation near the mid section of the forming table. The details of the effects of various parameters such as the slice profile and the flow rate at the side ejection valve are presented above.

In this section, we outline the method for capturing the secondary flows that are the source of nonuniform fiber orientation in the forming section. The secondary flows are weak relative to the main stream flow (i.e., flow component in MD) and, therefore, difficult to compute and visualize. Experimental measurements of these weak currents on the commercial machines are next to impossible. We have formulated a method to decompose the flow computationally into its primary and secondary components. From observing the secondary component of the flow, the physical mechanism of the cross-flow in the headbox can be better understood.

The method is to compute the flow field inside the headbox by excluding the effect of the side wall on the flow. This is accomplished by relaxing the no-slip condition of the side wall to the free-slip condition. The no-slip condition states that the fluid velocity adjacent to the side wall is the same as the velocity of the wall. In our case, the wall is stationary, and, therefore, the fluid velocity adjacent to the wall is zero. Because of this condition, the side wall imposes a shear stress on the fluid which results in boundary layer development and growth. The free-slip
condition states that although there cannot be any fluid penetration into the boundary, the surface does not impose a shear stress on the fluid. Let us refer to this case as the \textit{ideal} flow field since without the wall effect, the flow field will be two-dimensional (excluding the turbulent fluctuations). The secondary flow is defined as the difference between the real case, with no-slip boundary conditions at the side wall, and the ideal case. In other words,

\begin{equation}
U_s(x,y,z) = U(x,y,z) - U_i(x,z), \quad (1)
\end{equation}

where \( U \) represents the actual flow field with three velocity components \((u,v,w)\). The flow fields represented by \( U_s \) and \( U_i \) are the secondary and the ideal \((U_i = (u,w))\) flow fields, respectively. The contour plot of the cross-flow, \( v \), for the real flow field, \( U \), is presented in Fig. 25. As before, the left wall is a symmetry plane, and the other side is bounded by the no-slip side wall. We compute the ideal state using the same geometry and subtract it from the primary flow to get the secondary flow field. The secondary flow, \( U_s \), is visualized in Fig. 26 where the fluid particle trajectories are plotted inside the headbox. The top and side views are also presented in the same figure for better visualization.

The secondary flow forms a vortex inside the headbox with its source of energy concentrated near the side wall. To visualize this, we have computed the energy of the secondary flow inside the headbox by projecting the velocity field onto itself, that is

\begin{equation}
E(x,y,z) = \frac{U_s \cdot U_s}{U_{av}^2(x)} \quad (2)
\end{equation}

where \( U_{av}^2(x) \) is the square of the average mass flux at location \( x \) inside the headbox. The contour plot of the energy, \( E \), presented in Fig. 27, clearly shows the location of the source of secondary flow and, consequently, the cross-flow inside the headbox. In previous meetings we attributed the cross-flow to the boundary layer development and the shear exerted on the fluid from the side wall and the slice without providing any proofs. This analysis serves as a proof of our previous explanation of the physical mechanism generating the cross-flow inside the headbox.

In general, this method of analyzing the associated energy with the secondary flow is most effective in practical situations to \textit{pinpoint the source} of flow nonuniformities. Very often computation of the flow field alone will not readily reveal the source of the problem. The
Figure 25 The contour plot of the cross-flow, $v$, for the real flow field.
Figure 26 The fluid particle trajectories of the secondary flow.
Figure 27 Contour plot of the energy of the secondary flow showing the source of the mechanism generating cross-flow in the headbox.
method established here has proved to be most effective to pinpoint the origin of the flow nonuniformity inside a headbox.

10. THE EFFECTS OF ADDING VANES (CONVERFLO ELEMENTS) ON HYDRODYNAMIC CHARACTERISTICS, FIBER ORIENTATION, AND FIBER DISPERSION

Two headboxes are considered in this part of the project. A headbox with similar geometry as before is used as a reference to judge the effect of the partitions (converflo elements) on the flow characteristics. The second case has three partitions with the middle plate being longer than the top and bottom plates.

Figures 28a and 28b show the headbox configuration for the reference case and the three-partition case, respectively. Contour plots of the turbulent kinetic energy and the energy dissipation show the effect of the plates on the turbulence inside the headbox. It is interesting to note that the largest gradient in turbulent energy occurs at the tip of the elements. In general, a turbulent boundary layer develops on the surface of each element. However, since the flow between each element is in a converging section and the pressure gradient is negative, the boundary layer remains near the surface. In other words, the turbulent boundary layer will not effectively penetrate into the bulk flow until the separation between the elements becomes small near the slice (see the appendix for more details). Also, at the trailing edge of the elements, a mixing layer forms where the boundary layers on the top and bottom merge into a shear layer. This is where there is a maximum variation in the turbulent kinetic energy and dissipation rate. These results show that with our approach one can find an optimum location where the turbulent wake can be extended far enough to best maintain fiber dispersion and maximize formation characteristics. This is, however, beyond the objectives of our project for this year.

The average velocity vector plots in the headbox are shown for the two cases in Figures 29a and 29b. It is clear that the 'wake effect' of the elements persists up to the slice. This has no effect in terms of nonuniformity in the cross-machine direction. However, the maximum velocity in each section has decreased because of the partitions that are placed inside the headbox. Previously, we have established that if everything else is kept constant, increasing the jet velocity will increase the cross-flow. Because of the decrease in the streamwise velocity component, the overall effect of the vanes should be to reduce the cross-flow. This can be seen from the plot of the MD and CD velocity component at the slice shown in Figure 30, where the maximum cross-flow occurs. The results with the elements inside the headbox show a slight decrease in the cross
Contour plots of turbulent kinetic energy (top) and dissipation (bottom) in the headbox with no converflo elements.
Figure 28b  Contour plots of turbulent kinetic energy (top) and dissipation (bottom) in the headbox with three converflo elements.
Figure 29  Velocity vector plots inside the headbox with (a) no converflo elements, and (b) three converflo elements.
flow and the maximum streamwise velocity. These results are consistent with the previous conclusions.

Figure 30a. The stream wise velocity at various heights near the side wall.
Figure 30b. The cross-stream velocity at various heights near the sidewall.
11. CONCLUSIONS

To summarize the findings from Phase I of this project, we make the following specific conclusions:

1. Even in a headbox that is perfectly uniform and has perfect uniform influx through the tubes in the tube bank, the retardation of the flow at the edge of the tube bank alone will generate cross flows at the slice.

2. The cross flows at the slice result in nonuniform fiber orientation and mass formation.

3. Cross flows increase by increasing the side ejection flow rate at the 'cheeking piece bleed valves.'

4. Cross flows increase by decreasing the slice opening, assuming every other parameter remains unchanged.

5. Cross flows increase with nonuniformity of the slice profile.

6. The most effective way of removing the cross flow caused by the flow retardation at the side wall is to optimize the influx in order to compensate for the flow deficit and to cancel the side wall effects on the flow.

7. The most effective way to optimize the influx is to optimize the insert tube arrangement and size.

8. Influx variations in the Z-direction should be avoided.

9. The vanes (converflo elements) result in additional turbulent kinetic energy which would enhance formation. Adding the vanes to the headbox slightly reduces the streamwise velocity and, therefore, the cross flow and nonuniformity in fiber orientation. Once the influx is optimized to eliminate cross flow, then the converflo elements will have no effect in terms of CD nonuniformity.

These results show that geometry, size, profile, shape, and flow rate are all important parameters which need to be considered together in the analysis in order to evaluate and optimize a headbox.
reliably and accurately. The optimization method used with this approach has been verified to be effective in resolving nonuniform fiber orientations problems.

12. TASKS FOR PHASE II

The tasks proposed for next year are the most important part of this project. Currently we have established the source and mechanism for the hydrodynamically-induced nonuniformities inside the headbox. The proposed tasks are designed to establish the most effective mechanism for optimizing the headbox parameters in order to eliminate these nonuniformities.

Currently there is no information on the flow rate and flow characteristics in the tube bank for a given pressure as a function of the individual insert tube diameter or shape. This information is critical for optimization of the influx to reduce nonuniformities in fiber orientation and mass formation. We have identified the origin of the fiber orientation nonuniformities and the influence of various parameters on it. During the next year, we will complete the following tasks for optimization and elimination of this problem. The tasks for Phase II of the project are to:

(h) write a program for automatic mesh generation of the tube bank and the converging section of the nozzle for future computations

(i) compute the secondary flows at the slice that are generated by the interaction of the jets from the outlet of the tube bank into the headbox,

(j) analyze the effect of the tube arrangement on the secondary flows and determine the effect of swirling inside the tube on the flow at the slice,

(k) calculate the variation of the flow rate as a function of the pressure drop across the tube bank,

(l) compute the variation of the flow rate as a function of the individual insert tubes in a column of the tube bank,
13. PROJECT TIME TABLE FOR 1995

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14. SIGNIFICANCE TO THE INDUSTRY

The immediate value of the final results from this project to the industry is in terms of a better understanding of the hydrodynamic effects on fiber orientation in the forming section. This information can be utilized to control the polar angle and consequently improve properties such as twist-warp and crush strength.

In general, the computational analysis of flow in the headbox along with experimental high-speed flow visualization studies will provide the key information for improving formation in terms of paper and board properties. Uniformity or homogeneity of properties is perhaps the most desirable property in paper and board. This is precisely why a better understanding of the hydrodynamic instability in the forming section is so important to paper manufacturers. Jet roughness, large-amplitude wave formation, and spouting on the wire are other important issues which are beyond the scope of this project. In broad terms, this research aims at providing a better understanding of the effects of various flow characteristics on pertinent properties, and seeking techniques for improving the forming process in general to achieve higher productivity and better product quality.
ACKNOWLEDGMENT

The current project is being supported in part by the Containerboard and Kraft Paper Group of The American Forest and Paper Association. The Principal Investigator (PI: C.K. Aidun) acknowledges partial support from the National Science Foundation through the NSF/PYI grant CTS-9258667.

The PI appreciates the useful information provided by the CKPG Committee Members under the leadership of the previous chairman, Mr. Bob Guide, and current chairman, Mr. David South. In particular, we appreciate technical discussions and input from Mr. Neil Vander Linden, Mr. Bruce Babcock, and Mr. Lynn Jonakin. The years of experience complemented by the technical information acquired within the CKPG Committee members have made this project a success.

All of the members of the hydrodynamic instability and computational fluid dynamics team at the Institute of Paper Science and Technology are in some way contributing to this project. In particular, I acknowledge the outstanding efforts of Agnes Kovacs and Barbara Ericson, assisting me with the computations and pre- and post-processing. Also, I appreciate useful discussions with Marshall Hutten, Mac Hall, Dick Ellis, and Jim Challas.
APPENDIX

CHARACTERISTICS OF THE TURBULENT BOUNDARY LAYER
ON THE CONVERFLO ELEMENTS
In this section, we outline the general characteristics of turbulent boundary layer and apply the basic principles to the headbox with converflo elements.

At high Reynolds number flow along a flat surface, the influence of fluid viscosity is confined to a layer (i.e., a viscous boundary layer) near the solid surface. Boundary layers can be laminar or turbulent depending on the boundary layer Reynolds number and the surface characteristics. The two photographs presented in Figure A1 show the details of a typical turbulent boundary layer. The mushroom shape structures are typical turbulent eddies in a turbulent boundary layer (flow is from left to right, Photographs by R.E. Falco). These turbulent eddies scale with the wall variable, $z^+$, defined as

$$z^+ = \frac{zv^*}{v},$$

where, $z$ is the Cartesian coordinate normal to the wall, $v$ is the kinematic viscosity of the fluid, $v^*$ is the wall friction velocity and is defined as $\sqrt{\frac{\tau_w}{\rho}}$, $\tau_w$ is the wall shear stress, and $\rho$ is the fluid density.

A typical boundary layer thickness could be about $z^+=1500$ and since the eddies scale with the wall variable, their size is very small relative to the boundary layer thickness. Their small scale provides a very effective mechanism for dispersing the fibers in the fluid. This is the reason that turbulent boundary layers are effective in fiber dispersion. However, the effective dispersion occurs only inside the boundary layer where these eddies reside. Therefore, the success of the converflo elements depend on two effects, (1) forming a turbulent boundary layer and (2) 'thickening' the turbulent boundary layer to allow effective dispersion of the fibers in the bulk flow.

Almost always, the section between the converflo elements inside the headbox is a converging channel with negative pressure gradient. This forces the turbulent boundary layer to remain confined in a thin region near the walls, as shown in Figure A2 (flow is from left to right, photographs by R.E. Falco). In contrast, with an adverse pressure gradient, the boundary layer
separates from the wall and penetrates into the bulk flow, as shown in Figure A3 (flow is from left to right, photographs by R.E. Falco).

If near the slice, the channel height decreases to within the boundary layer region, then fiber dispersion would be most effective. However, we should also note that very often the favorable pressure gradient in a converging channel may result in relaminarization of the turbulent boundary layer, as is demonstrated in Figure A3.
Visualization of the mushroom-shaped eddies inside a turbulent boundary layer which result in an effective mechanism for fiber dispersion.
Figure A2  Turbulent boundary layer in a converging channel (favorable pressure gradient)

Figure A3  Turbulent boundary layer in a diverging channel (adverse pressure gradient)