

The influence of headbox flow conditions on paper properties and their constancy

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ABSTRACT *Certain design parameters and operating conditions of the headbox lead to flow conditions at the slice and on the wire resulting in a displacement of the main fiber orientation in the xy -plane away from the machine direction. For some paper grades, this means potential problems in subsequent converting operations and in product end use (diagonal curl). The phenomenon is explained by a simple fluid model. Results from tests with commercially installed Step Diffusor headboxes are reported. These tests showed the effect of variations in distributor overflow and local slice bar adjustment on local main fiber orientation across the machine. Results of measures in both headbox design and in facilitating operation show distinct improvements in fiber orientation.*

KEYWORDS

Fiber orientation
Formation
Headboxes
Paper properties
Turbulence

One essential task of the paper machine headbox is the controlled distribution of the stock onto the wire to ensure optimum uniformity of various quality properties in both the machine direction and the cross-machine direction. Basis weight distribution and fiber orientation in the xy -plane of the web are strongly influenced by the headbox operating parameters.

Fiber orientation in the web influences the MD:CD tensile ratio, for instance, which is usually measured in the laboratory for production control. However, increasing demands in converting operations and in product use for certain paper grades have shown that in some cases this type of physical test is not sufficient for accurately determining and evaluating the existing problems (1, 2).

On analyzing curl problems in which the curl axis is not exactly in the machine direction, we find that the measurement of the main fiber orientation supplies the key to explaining and often solving this type of quality problem. Here, we will describe potential origins of the displacement of the

main fiber orientation away from the machine direction. We will also present typical results from mill operations and show the strategy for CD basis weight control with an acceptable degree of nonuniformity in the main fiber orientation. The associated headbox design strategy will also be described.

All results from theoretical and experimental studies presented here were obtained with a fourdrinier-type wet end. However, these results can be extrapolated to different types of formers, such as hybrid or gap twin-wire formers.

General approach to the main fiber orientation problem

Causes of main fiber orientation defects

A requirement for good headbox operation is that the slice flow conditions be uniform at all positions across the machine width in terms of throughput and jet velocity. The angle between the stock jet and the machine direction in the xy -plane is critical for the direc-

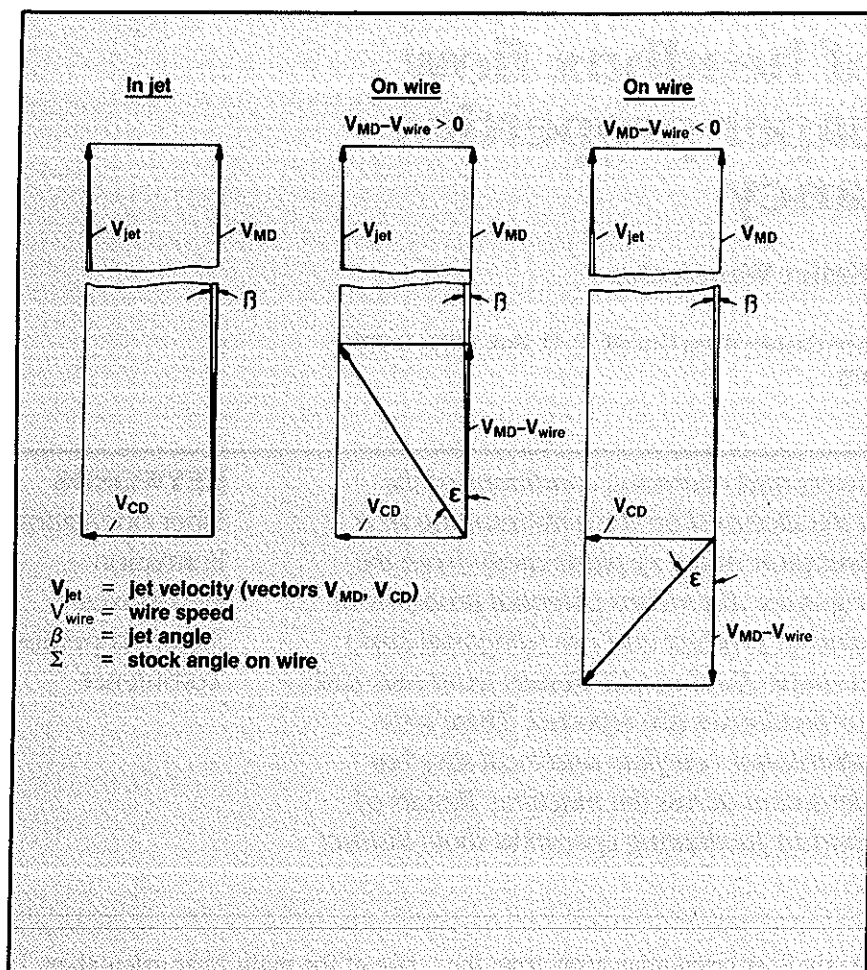
tion of the main fiber orientation. In practice, angles of main fiber orientation are found that are large (up to 10°), although these large angles could never be observed or measured in the free jet when running the headbox at normal operating conditions.

This contradiction can be explained by a simple vector analysis. **Figure 1** shows that a small jet angle can lead to a considerable jet velocity in the cross-machine direction. At a speed of 600 m/min (2000 ft/min), for example, an angle of only 0.1° gives a CD component of approximately 1 m/min (3 ft/min).

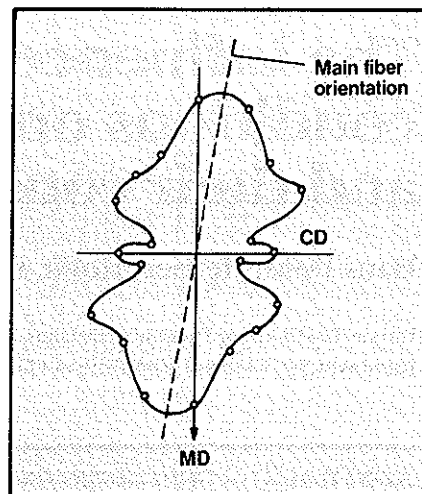
Once the jet has impinged on the wire, the only remaining MD velocity vector in the wire-stock combination is the differential velocity between the stock and the wire.

The CD velocity vector on the wire, however, remains just as large as in the free jet. In this example, a differential velocity setting of 6 m/min (20 ft/min) with a constant CD velocity of 1 m/min (3 ft/min) would lead to a flow angle on the wire of approximately 10° . The angle is thus increased by a

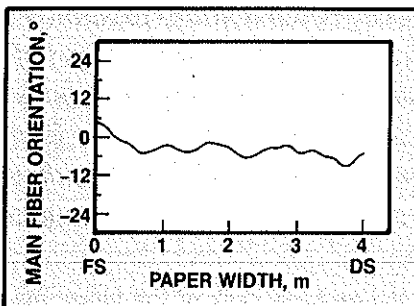
1. Stock velocity vectors in the jet and on the wire



2. The main fiber orientation in the xy-plane can be determined by counting marked fibers and plotting fiber angles in polar coordinates.



3. A plot of a laser-based measurement of local main fiber orientation across the machine (writing and printing paper, 80 g/m², average MD:CD tensile ratio = 2.3, FS = front side, DS = drive side.)



factor of 100! The relative motion between the stock and the wire and its developing fiber mat causes the fibers to align mainly in the direction of this motion. Thus the angle of highest relative motion defines the angle of main fiber orientation.

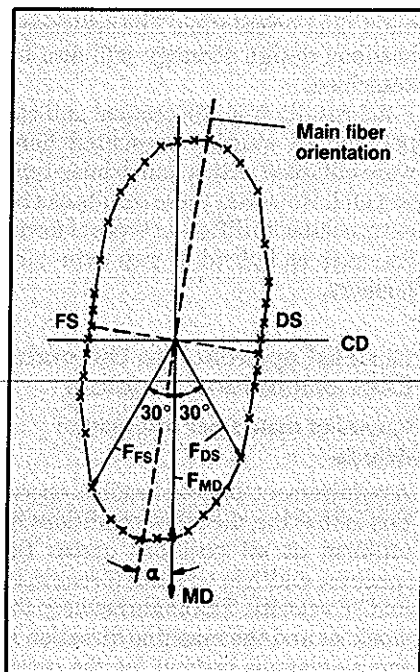
This analysis shows that the angle of main fiber orientation depends both on the CD component in the jet velocity and on the relative MD velocity between the jet and wire. During the transition from rush to drag, the angle of orientation must therefore turn around, as shown in the far right illustration in Fig. 1.

Slight differences in the jet:wire ratio and/or small variations in the jet angle may result in strong deviations in main fiber orientation across the machine width.

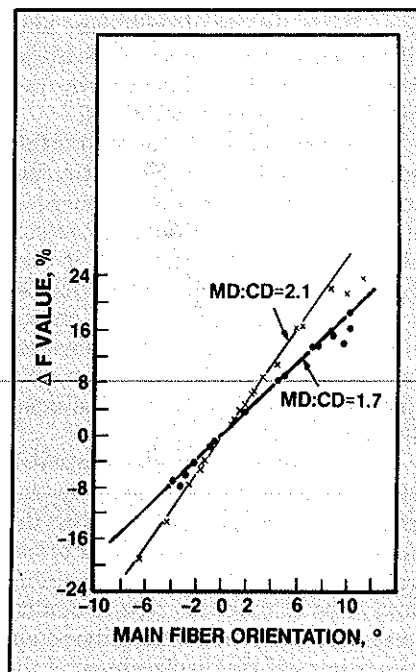
Methods for measuring main fiber orientation

Good basic data on main fiber orientation in the *xy*-plane can be obtained by

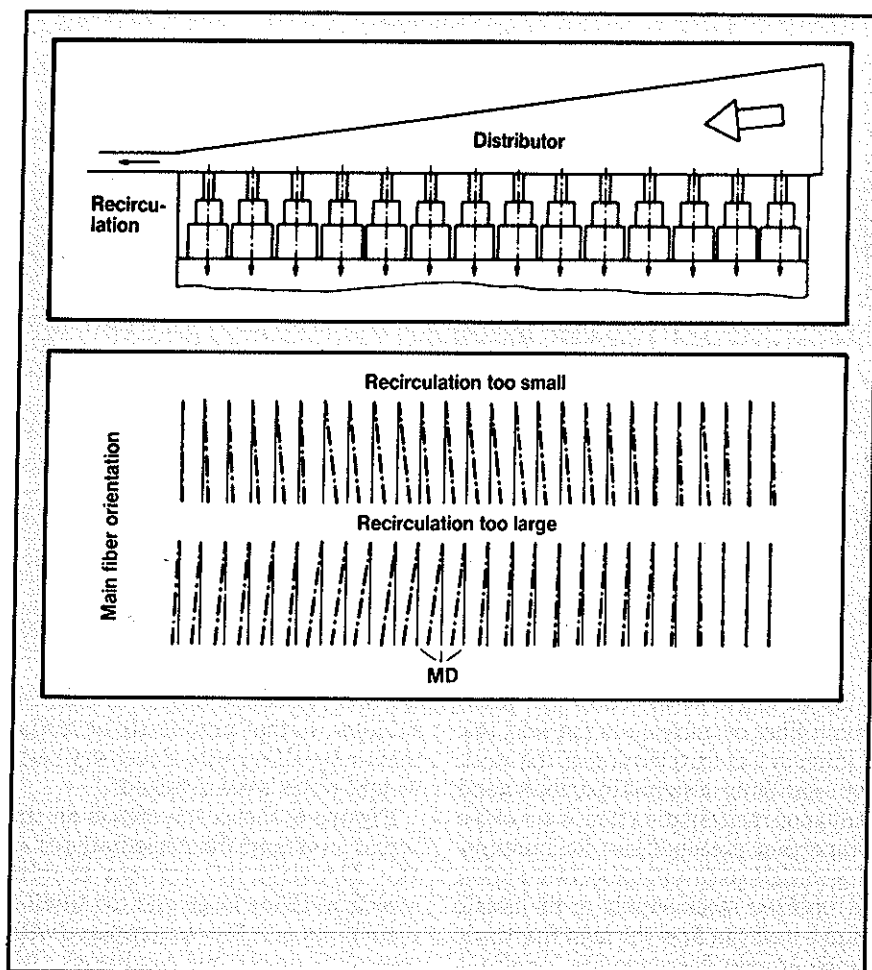
4. Example for determining the main fiber orientation in the *xy*-plane by measuring tensile strength



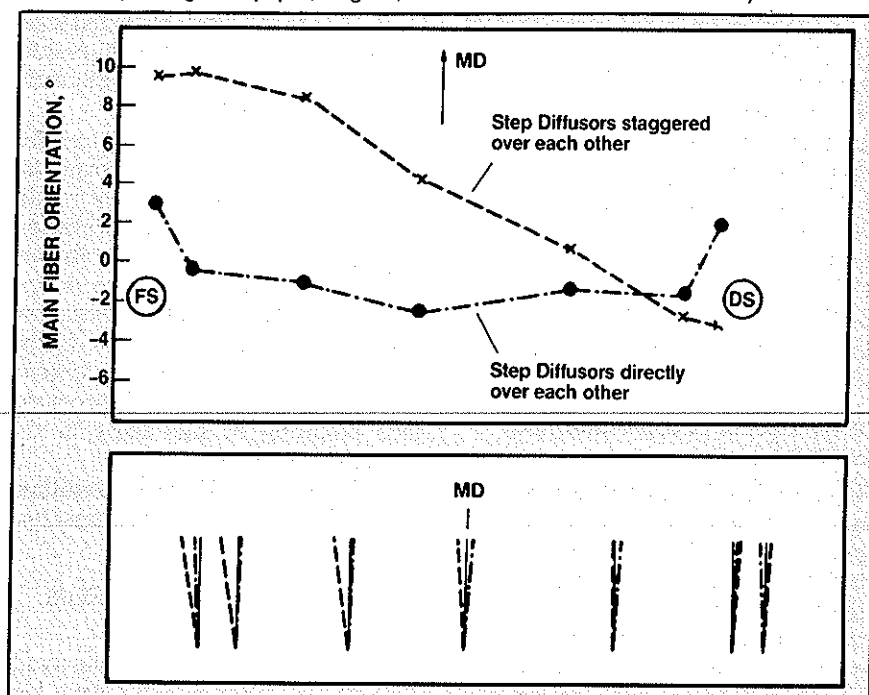
5. Comparison of ΔF values and calculated angles of main fiber orientation for different MD:CD ratios



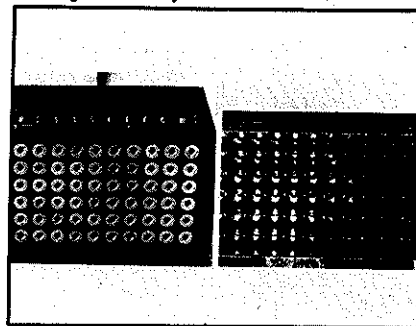
6. Variation of main fiber orientation with overflow settings too small and too large (parameters as in Fig. 2)



7. Main fiber orientation relative to the machine direction for differently arranged Step Diffusors (coating base paper, 50 g/m², constant mean MD:CD tensile ratio)



8. Step Diffusor block with Step Diffusors arranged directly over each other



counting marked fibers and their angles in the sheet (1). Figure 2 shows the frequency distribution of fiber angles as plotted on polar coordinates. In this particular case, the main fiber orientation shows an angle of approximately 10°. Although counting marked fibers and their angles is time-consuming, it is the only simple way of measuring the main fiber orientation in different layers of the sheet where this orientation differs through the sheet cross section.

Optical (3-5) and acoustic (6-9) methods of determining main fiber orientation are now available for measurements in the laboratory and in commercial operations. These techniques measure a mean value of fiber orientation. Figure 3 shows a plot of a laser-based measurement of local main fiber orientation across the machine width.

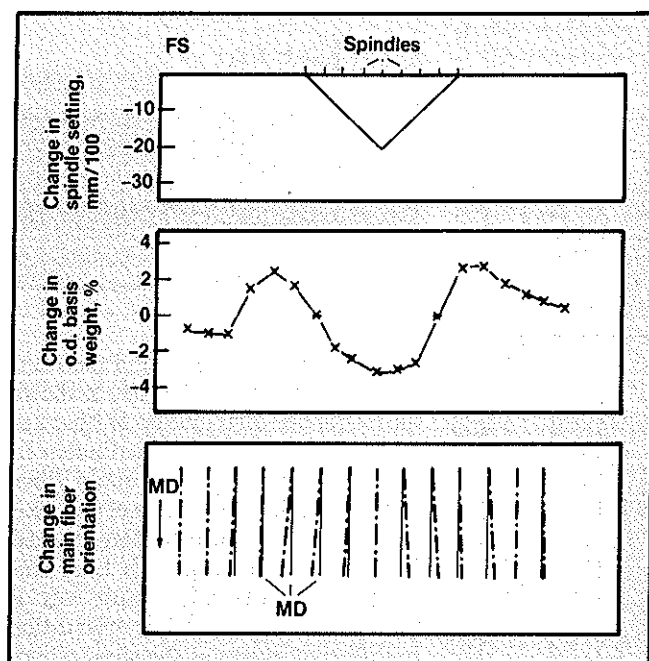
When these studies were carried out, the only method of determining main fiber orientation that could be considered at the same time was that of measuring tensile strength. This type of measurement also gives a mean value of main fiber orientation through the sheet cross section.

In Fig. 4, tensile strength measurements in different directions in the *xy*-plane are plotted on polar coordinates. This curve is a good approximation to an ellipse, at least in the range of the long main axis, which is defined as the main fiber orientation.

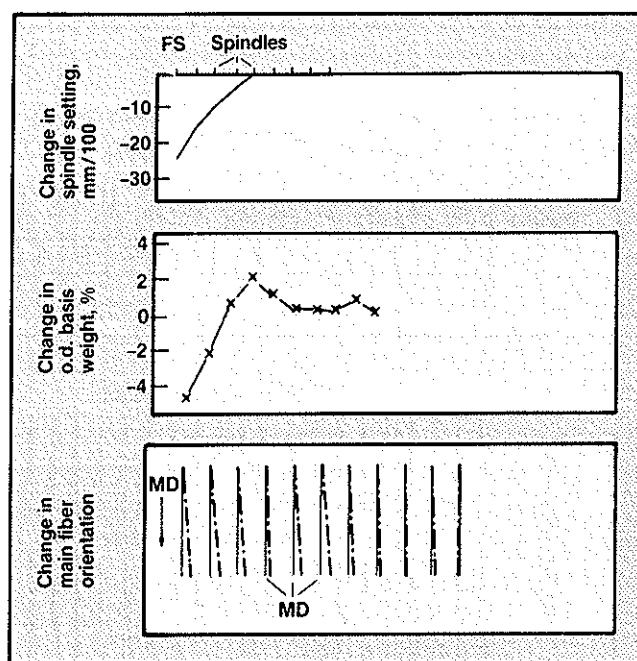
There are various ways of determining main fiber orientation from tensile strength measurements. For instance, from the pattern of tensile strength shown in Fig. 4, the main fiber orientation can be estimated by visually comparing areas, although this method is time-consuming.

Another method is to calculate the main fiber orientation from the ellipse equation, where tensile strength is measured in three directions. Apart

9. The change in main fiber orientation and in o.d. basis weight profile by local slice adjustment in the center (parameters as in Fig. 2)



10. The change in main fiber orientation and in o.d. basis weight profile by local slice adjustment at the edge (parameters as in Fig. 2)



from MD tensile strength, two tensile strengths should be used at an angle of, for example, 30° to the front side (FS) and to the drive side (DS) of the machine, respectively.

Good correlation was obtained between the main fiber orientation angles as determined both by visual observation and by calculation.

The amount of measurement work can be reduced by one third if only the two tensile strength measurements at 30° to the front and drive sides of the machine are used for computing the ΔF value. This value is defined as

$$\Delta F = 100 (F_{fs} - F_{ds}) / (F_{fs} + F_{ds}) / 2 [\%] \quad (1)$$

Figure 5 shows that for a constant tensile strength ratio, good correlation is obtained between the ΔF value and the main fiber orientation when the orientation has an angle of not more than 10°.

With production conditions constant in the jet:wire velocity ratio, the determination of the ΔF value is thus a good way of quantifying deviations from the main fiber orientation. The diagram shows that, as expected, for the same main fiber orientation angle the ΔF value rises with increasing tensile strength ratio.

Headbox design, operating parameters, and main fiber orientation

All parameters influencing jet velocity

and jet angle at the slice can affect main fiber orientation in the web, too. Uniform CD distribution of the stock by a carefully designed distributor and adjusted recirculation flow is one of the important preconditions for minimizing deviations in main fiber orientation. A uniform stock supply to the nozzle and a uniform flow through the nozzle without side flows are also required. Ideally, the jet exits the nozzle with a uniform velocity and a direction exactly parallel to the machine direction across the full headbox width.

In practice, total uniformity of flow conditions can never be obtained. But knowing the principles of how to influence the jet flow conditions can help to improve paper quality in regard to main fiber orientation.

Numerous tests on commercial paper machines with Step Diffusor® headboxes have been performed to quantify the effect of the important parameters on the direction of main fiber orientation. Basically, the results also apply to all types of headboxes.

The influence of distributor flow conditions

The critical influence of pressure conditions in the distributor was confirmed by a test in which pressure distribution in the distributor was altered by varying the recirculation flow. The small throughput deviations across the machine width through the Step Diffusor block were compensated for by a rela-

tively slight adjustment of the control spindles, so that practically no deviations in the CD profile of oven dry basis weight pulps were detected.

Figure 6 shows the effects on the direction of main fiber orientation (i.e., the direction of highest tensile strength) of too large and too small a distributor overflow as compared with optimum operating conditions. All other parameters were kept constant. Too large an overflow results in a clear orientation in the overflow direction. Too small an overflow has the opposite effect. The tests were performed with an efflux ratio on the rush side, resulting in a MD:CD tensile strength ratio of approximately 2.3.

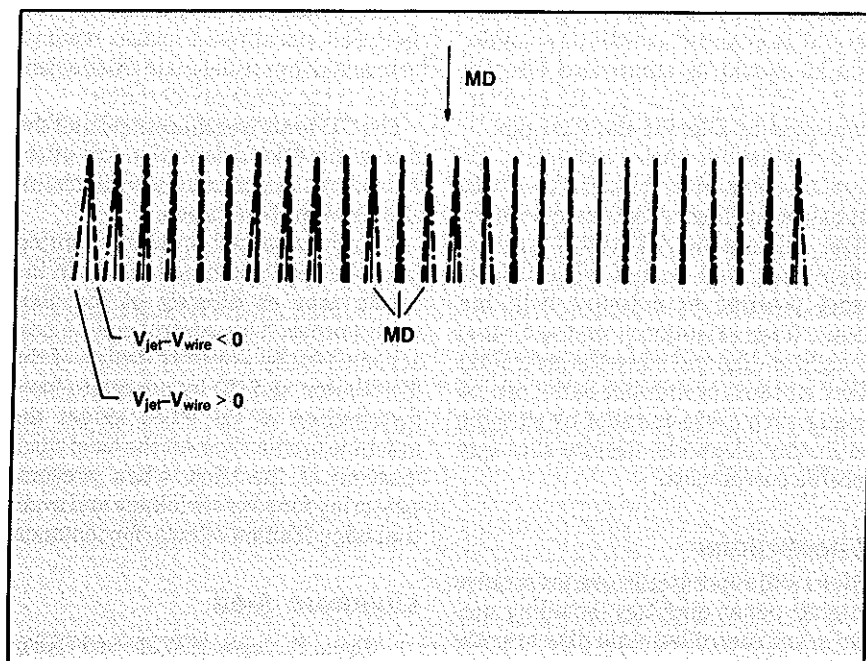
The effect can be explained as follows. Increasing the overflow over and above the optimum operating conditions results in a steadily decreasing static pressure across the distributor. A decreasing static pressure means decreasing throughput across the width of the distributor block. In the nozzle area, however, the flow tries to reach an equilibrium of static pressure, thus resulting in side flows in the nozzle and in the jet.

The figure shows the actual resultant change in the direction of highest tensile strength.

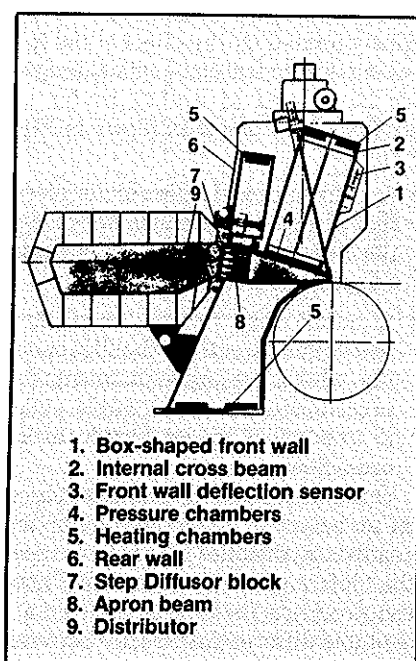
The influence of distributor block uniformity

Many of the distributor blocks available on the market so far have less

11. Reversal of main fiber orientation when changing jet velocity from rush to drag (parameters as in Fig. 2)



12. Schematic drawing of a Step Diffusor headbox



open area at the extreme edges because of a staggered arrangement of the individual turbulence generation elements. Up to now, this has been the usual design technology for blocks because measurements of paper characteristics, especially basis weight, showed no unacceptable deviations in the edge zones. The only noticeable alteration was in CD stretch resulting from shrink variations during drying.

However, ongoing research work has shown that the main fiber orientation can also be affected by this staggered arrangement because it causes cross flows in the nozzle and in the free jet towards the front and drive sides. Figure 7 shows an example of main fiber orientation produced with the previous type of Step Diffusor block. The main fiber orientation towards each side is visible (in the angle directed to the front side at the front side end and in the angle to the drive side at the drive side end).

Today's advanced design of stainless steel Step Diffusor block avoids this problem. As shown in the diagram, almost all the deviations in main fiber orientation at the sides have been eliminated. All other conditions had been kept the same as before.

Figure 8 shows the construction of the new generation of Step Diffusor block where the elements are now arranged directly on top of each other to minimize the disturbances at the sides. The uniform velocity and turbu-

lence profiles of the Step Diffusor and a maximum open area at the flow exit side result in a homogeneous flow at the slice. This homogeneity serves to avoid the problems of streak formation in the paper, as confirmed in practice for critical paper grades. With today's block design, the inlet diameter and the two stepped enlargements continue to be defined by precision inserts of a special synthetic material.

Influence of local slice gap adjustment

Local variations in slice opening also have an influence on the jet flow pattern. Where the slice opening is locally reduced, cross flows are found, leading away from the place of local slice reduction. Increases in the local slice gap result in a cross flow towards the place of slice increase.

Figure 9 shows the effect of local slice reduction on basis weight and on main fiber orientation. The upper part of the diagram shows the local variation in spindle setting. In the middle of the diagram, the effect on the CD basis weight profile is illustrated. In the bottom part, the local change in direction of highest tensile strength of paper relative to the machine direction is plotted for a particular section of the machine width.

If the slice gap has to be reduced at the edges, to precompensate for edge shrinkage during drying for instance, the effect on main fiber orientation

may show up as indicated in Fig. 10. The flow at the edge is oriented in this case towards the machine center. The influence on the basis weight profile and on main fiber orientation is similar, but the range or width of influences at the edge is larger than with symmetrical adjustments closer to the center.

The influence of drag and rush

As mentioned, jet operation with drag or rush influences the direction of main fiber orientation. Without changing any of the other settings, two different jet velocities were set alternatively on a paper machine, first with rush and then with drag. Figure 11 shows that in both cases the main direction of fiber orientation altered in the expected manner.

All of the results, especially those in this last example, prove that the model presented here to describe the causes of variations in main fiber orientation is close to reality.

Requirements for optimum headbox design and operation

Because of the strong interdependence of the CD basis weight profile control and the CD main fiber orientation profile, a new set of requirements for headbox design and operation is needed wherever main fiber orientation is a vital quality property. To meet these high quality demands, the individual

flow streams through the headbox nozzle have to be close to exactly parallel.

In practice, this ideal can be closely approximated by the effect of the following design features, which designers have tried to realize as far as possible in the headbox shown in Fig. 12 (10):

- A distributor and a distributor block that locally feeds as much stock from the block as locally exits at the same CD position from the slice
- A nozzle that reduces cross flow before and directly at the slice opening, when slice gap adjustments for precompensation, for example, make it impossible to completely avoid cross flows.

Optimum operating conditions based on an accurate understanding of the headbox hydraulics also help to meet the high quality requirements. These requirements include the highest acceptable differential velocity between the jet and the wire to reduce the angle of main fiber orientation away from the machine direction. Second, the distributor recirculation flow setting should be chosen to give optimum

pressure distribution in the nozzle, and nozzle pressure difference between the front and drive side should be measured. Finally, the slice gap profile should be changed as little as possible. Faults should be eliminated directly at their source, instead of with precompensation by altering the slice gap.

By following these measures, all quality demands currently known to us can be fulfilled with respect to main fiber orientation. Additional requirements can only be met when it is at least possible to measure both the main fiber orientation and the basis weight on-line and when the individual flow streams at the slice outlet can be made even more parallel by suitable adjusting elements, despite slice gap profile corrections.

Conclusions

More and more paper grades require higher paper qualities including uniform and controlled main fiber orientation (with the curl axis parallel to the machine direction) to avoid uncontrolled curl problems in converting operations or in product use.

Main fiber orientation with an angle

to the machine direction of other than zero is caused by cross flows at the slice which are amplified on the wire.

Certain headbox design features and operation parameters cause nonuniform and nonparallel main fiber orientation to the machine direction.

The CD basis weight control and the local main fiber orientation are interdependent, as demonstrated in examples from mill operation.

To minimize curl problems coming from the headbox, no side flows in the nozzle near or directly at the slice should occur. This control can be best achieved (a) by accurate design of the distributor and (b) by adequate local distribution of the stock across the machine to exactly meet the local stock demand at the slice, when precompensating for edge shrinkage and eventual edge friction effects, for instance.

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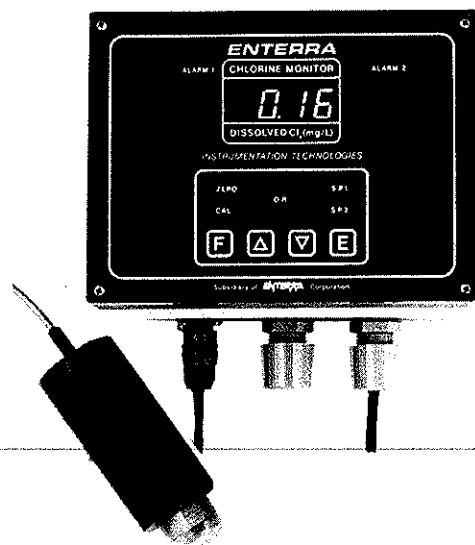
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