

Hydrodynamics of streaks on the forming table

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UNIFORMITY OF PHYSICAL PROPERTIES of paper manufactured for printing, packaging, and other applications continues to be one of the most serious quality issues in today's mills. Quality issues, such as the small-scale variations in basis weight, density, and fiber orientation, will become considerably more important in the mill of the future. The reason is threefold: (a) continuously increasing demand for higher quality by the consumer, (b) new technologies in consolidation, finishing, and converting, and (c) the requirement to be more efficient (e.g., have less rejects) and more productive.

The fundamental physical characteristics of paper are the physical properties of the fiber, the fiber network including density and fiber orientation, and the basis weight or the weight per unit in-plane area of the sheet. The entire sheet characteristics and behavior are based on these fundamental properties. Uniformity of basis weight, density, and fiber orientation are of highest immediate importance, since many other physical properties are influenced to various degrees in the forming process based on these fundamental characteristics.

Two of the three fundamental physical properties of paper and board outlined above, i.e., the fiber network structure and the basis weight, take form in the headbox and on the forming table. This is the reason that many experienced papermakers believe that the headbox and the forming table are the most criti-

cal process in paper forming. In fact, one of the highest priority research needs in papermaking processes has been identified as "improved understanding of the fundamentals of sheet formation..." such as "...turbulence, flocculation, stock jet velocity and impingement angle, wet-end process measurements..." (1).

The large-scale average basis weight and moisture profile variations (i.e., variations with a span greater than 6 in. in the cross direction) can be controlled effectively with today's technologies. However, small-scale physical property variations that range from 0.5 to 4 in. in span are often not detected on-line and, consequently, are not controlled. There is also considerable evidence that these small-scale nonuniformities in physical properties cause many problems in converting and printing. Paper rejects due to quality issues are of common concern in today's mills. Furthermore, the success and effectiveness of new technologies in high-intensity drying, high-moisture calendaring, and high-quality coating greatly depend on the uniformity of fundamental physical properties in the base sheet.

SMALL-SCALE VARIATIONS IN PHYSICAL PROPERTIES

High resolution measurements with more than 30 points/in. (2) show that, in most of today's commercially manufactured paper and board, there are small-scale basis-weight variations ranging from 5 to 20%, with peak-to-peak cross-direction spans of 0.5–4 in. We have not seen high-resolution

ABSTRACT

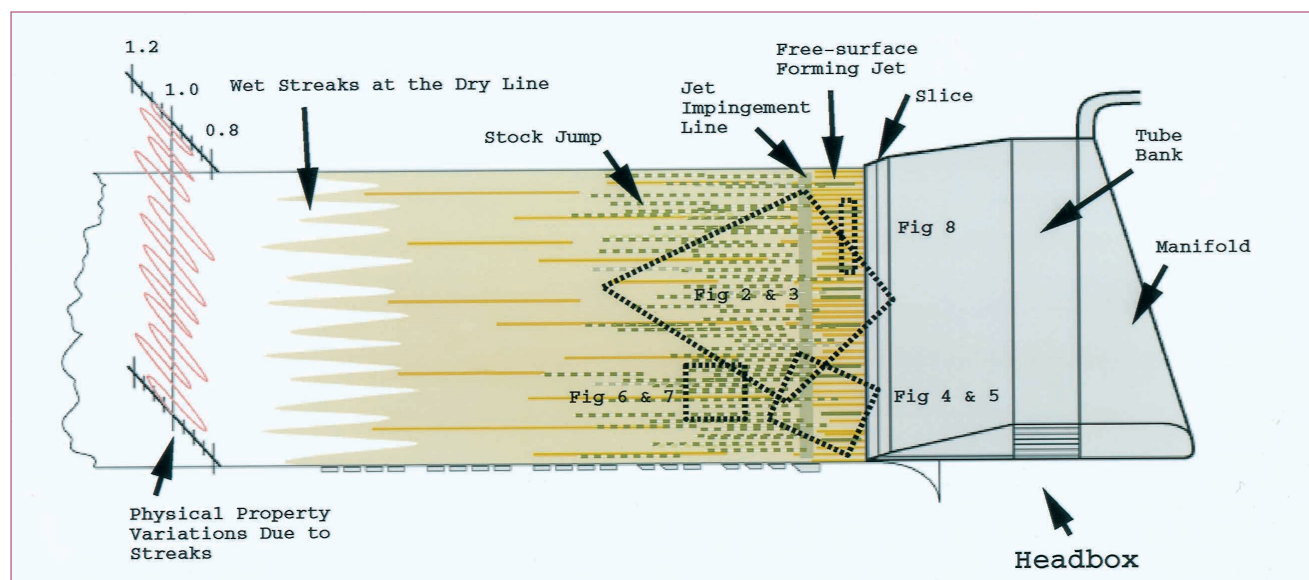
In today's commercially manufactured paper and board, there are small-scale basis weight nonuniformities ranging from 5 to 20%, along with small-scale fiber orientation and density nonuniformities, which are generally much larger. Nonuniformities in basis weight and sometimes the variations in moisture originate in the forming section due to the small-scale secondary flows and streaks in the forming layer. Some believe that the streaks in the forming jet and on the forming table are caused by the turbulent fluctuations inside the headbox and on the forming table. In this paper, we show that the streaks are not caused by random turbulent fluctuations. In contrast, streaks in the forming section are deterministic and originate in the headbox due to small-scale secondary flows. The secondary flows are generated, in part, by the interaction of the jets from the tubes in the tube bank and in some instances are due to secondary flows though the tubes or other parts of the headbox.

The methods presented in this paper help in understanding the paper-forming process and, consequently, improving the product quality.

Application:

Applications include optimization of the forming hydrodynamics to improve quality and productivity.

basis-weight measurements of any commercially produced sheet with less than 5% variation. There is considerable evidence that relatively large variations in other physical properties, such as fiber orientation and sheet density, are present over the same length scale. The magnitude of the small-scale variations is much larger than the measurements provided by the low-resolution on-line sensors.



1. Streaks on the forming table. Locations of the images presented in Figs. 2–8 are outlined.

Variations in basis weight and moisture streaks could have many causes. We categorize these into three classes: (a) nonuniformity in fiber concentration or consistency, (b) nonuniformity in mass distribution on the forming wire or forming table, and (c) nonuniform drainage in the forming section. Of these, we are concerned with the second and third mechanisms, i.e., the dynamics of the formation process. The hydrodynamics of the headbox, the characteristics of the free-surface forming jet, jet impingement, and the evolution of the layer along the forming section are the key parameters that will be discussed. The possible nonuniformities caused by the structural defects in the headbox and the forming section are another issue that will not be discussed in this paper.

The smaller-scale variations in basis weight, considered here, are not well understood and, therefore, are more difficult to eliminate. In this study, we focus on the class (b) and (c) causes of small-scale basis weight nonuniformity, as outlined above.

The magnitudes of the small-scale fluctuations in basis weight are often considerably larger than the magnitude of the basis-weight variations recorded by the on-line sensors. Since the performance and

strength of the product usually depend on the magnitude of the variation in physical properties, the small-scale fluctuations could be more important than the overall averaged nonuniformities. The small-scale fluctuations in elastic stiffness can be caused either by variations in the local sheet density, by small-scale variations in fiber orientation, or by the nonuniform drying rate due to moisture streaks in the sheet. These nonuniformities can be caused by streaks in the forming section.

Are streaks on the forming table the result of random turbulent fluctuations or deterministic secondary flows? To answer this question, in the next section we analyze the streaks on the forming wire.

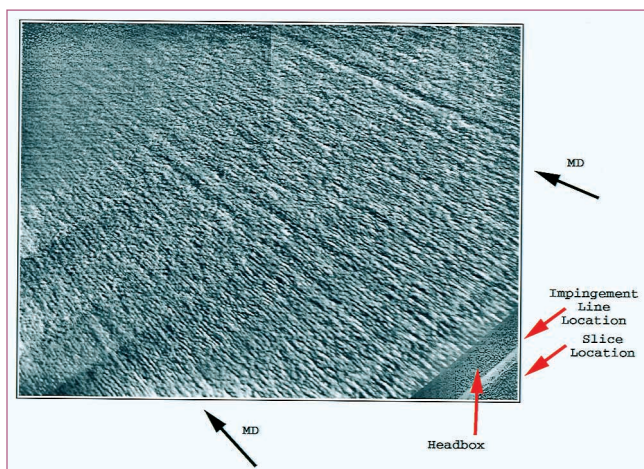
EVOLUTION OF STREAKS ON THE FORMING WIRE

Turbulent flow, by definition, is a combination of high-frequency undeterministic random flow fluctuations superimposed on a deterministic mean flow. The time-frozen snapshot of the velocity profile in a turbulent flow shows many fluctuations with an average trend. If a large number of the instantaneous turbulent profiles are added and averaged, then a smooth profile, referred to as the *mean turbulent profile*,

emerges. In other words, turbulent fluctuations are random occurrences in time superimposed on the mean flow. In contrast to the random turbulent fluctuations, the mean turbulent profile is a deterministic or predictable quantity.

To understand the flow in the forming section over a scale larger than 0.5 in., we need to focus on the mean turbulent flow on the forming wire. The turbulent fluctuations in the flow are also very important in terms of formation and effects on the evolution of streaks.

Detailed high-speed digital imaging of the forming table is one of the methods that we use in our program to study the physics of paper forming. The high-speed images can be taken at up to 4000 frames/second, with an exposure time as short as 1 μ s. The small exposure time of a single frame captures the forming layer in a time-frozen form, showing the details of the small-scale fluctuations due to turbulent flow. An example of this approach will be presented here with analysis of various regions of the forming section, as outlined in **Fig. 1**. A single frame of the flow over a large section of the forming table is shown in **Fig. 2**. The machine speed is 3000 ft/min, making base sheet for a coated grade. In



2. Time-frozen image of the flow over the forming table. The slice and the impingement line are not visible in the image. Their general location along with the machine direction are shown in Fig. 1. (Machine speed = 3000 ft/min. Exposure time of the image = 50 μ s).

this view, the slice and the impingement line are covered by the headbox, as indicated in the figure. This image shows many small-scale fluctuations on the forming table. A time-frozen image, as indicated below, is a superposition of randomly occurring flow fluctuations on the mean flow. However, from this image, it is not clear whether there are consistent regularly patterned streaks on the forming table. To examine this, we need to remove the random fluctuations and look at the mean flow.

By averaging these images over several hundred frames, we can remove the small and randomly occurring feature from the image and examine the mean flow. Since the images that we obtain are in digital form, we have developed methods to greatly enhance the image and to take the average of a specific number of images (9).*

For this machine speed, an exposure time of 50 μ s is found to be sufficient. The average flow over 500 frames, each with an exposure time of 50 μ s taken at a rate of 1000 frames/second covering 0.5 seconds in real time, is shown in Fig. 3. This image clearly shows that there is a

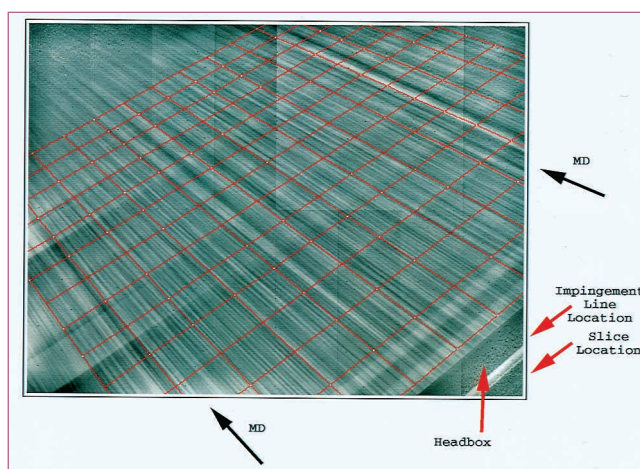
consistent streak pattern in the mean flow over the forming table. To determine the length scale of the streaks, a grid line with tic marks is superimposed on the image. Each division represents 12 in.

The imaging method used here shows that there is a consistent streak pattern present on the forming table. In a time-frozen image, this pattern is not clearly visible because of the random fluctuations that are superimposed on the mean flow. Once the random fluctuations are removed, the streaks become clearly visible, as demonstrated previously.

CHARACTERISTICS OF JET IMPINGEMENT AND STOCK JUMP

As the forming jet delivered from the slice impinges on the wire, the variations in the free surface height (in other words, the free surface waves or disturbances) magnify due to the variation of the acceleration normal to the free surface. [The physics is similar to the Rayleigh-Taylor instability (3-6).] The magnification of the disturbances increases with the magnitude of the acceleration or the jet angle.

The top view of a typical stock jump is shown in Fig. 4, where the machine direction is from right to left in the figure. This is a single frame taken directly from the top of the wire immediately after the



3. Average of 500 images of the forming table shown in Fig. 1, covering a period of 0.5 seconds. The red lines show a 12-in.-long scale in the machine and cross directions.

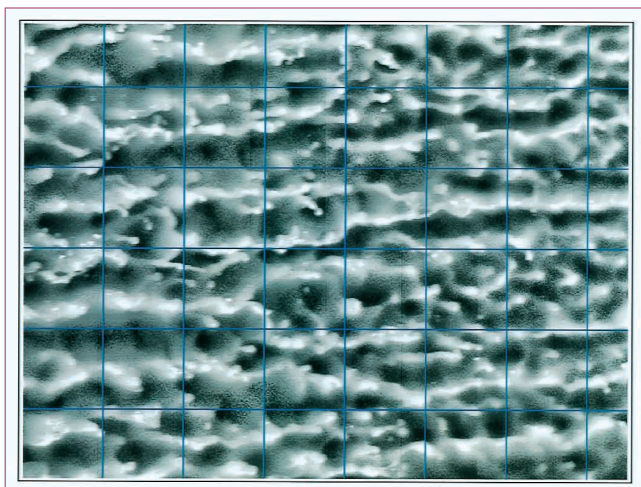
impingement line. The question is whether one can eliminate the streaks on the forming table (see Fig. 3) by strong disturbance of the forming jet and creation of large stock activities at the impingement region. By averaging the top-view images of the stock activity after the impingement line, as shown in Fig. 5, we examine the character of the flow in this region. It is clear from this figure that the mean free-surface flow of the forming layer at the post-impingement line is nonuniform. A regular streak pattern develops in the mean flow, even with severe stock jump. This clearly demonstrates that, at least in the situations examined in this study, the regular stock activity on the wire cannot eliminate the streaks in the forming jet.

In the next section, we discuss the origin of these streaks.

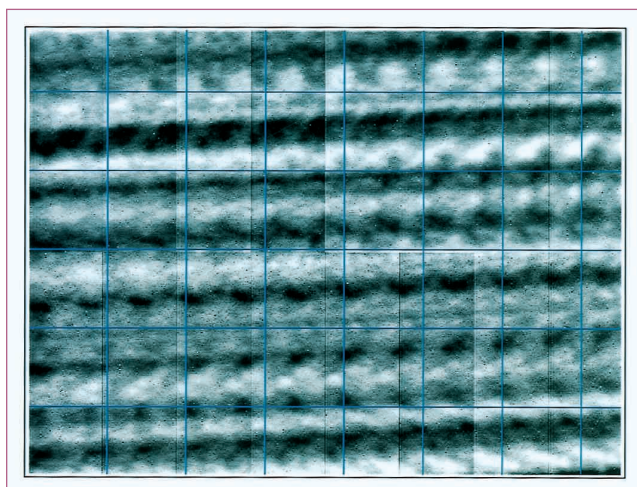
ORIGIN OF STREAKS AND NONUNIFORMITIES IN THE FORMING SECTION

Let us take a closer look at the forming jet delivered at the slice. The enhanced time-frozen image of the forming jet and the impingement line is shown in Fig. 6. This image clearly shows streaks in the forming jet that amplify upon impingement on the forming wire and result in some degree of stock jump. Some believe that the streaks in the forming jet are due to the turbulent fluctuations inside the headbox and,

*The averaging method used here is not to be confused with the long-time exposure methods. With long-time exposure, a moving point will leave a continuous streak on the image. With our method, a moving point leaves N number of points on the image, each with a gray level intensity of $1/N$ of the original intensity, where N is the number of frames used in the process.



4. Time-frozen top-view image of the stock jump after the impingement line. The machine direction is from right to left of the image. (Machine speed = 3000 ft/min. Exposure time of the image = 50 μ s).



5. Average of 100 images of the top-view image of the stock jump after the impingement line shown in Fig. 4, covering a period of 0.1 seconds. The blue lines show a 1-in. grid line. The machine direction is from right to left of the image.

therefore, occur randomly in the system. To examine this point, we again take an average of the flow over 0.5 seconds. The averaged image is presented in Fig. 7. It is clear from the averaged result that the streaks appear consistently, not randomly, in the forming jet. Turbulent fluctuations, however, appear randomly. Therefore, the streaks in the forming jet are not the result of turbulent fluctuations.

Using large-scale computational methods, we show (in the 1996 IPST report to member companies) that different forms of small-scale secondary flows result from the interaction of the jets from the tubes in the tube bank. The nature of the secondary flows depends on the geometry and size of the tubes and their arranged pattern in the tube bank.

Now consider the jets that are delivered by these tubes. The streaks in the forming jet, such as those in Fig. 7, are caused by the secondary flows induced by the jets from the tubes. These secondary flows are spatially periodic in nature. That is, there is a given cross-direction span over which the structure of the flow pattern repeats. We can refer to the cross-direction dimension of this periodic pattern as the width or the wavelength of the secondary flow. The wavelength of the tube

jet-induced secondary flow is not necessarily equal to the cross-direction spacing of the tubes in the tube bank. The secondary flows often appear in the form of recirculating vortices, which are superimposed on the main stream flow. Secondary flows, not to be confused with turbulent fluctuations, are deterministic parts of the flow generated by various mechanisms and can be computed using the mean form of the momentum equation and appropriate turbulent models (7, 8).

These secondary vortices, once relieved from the confined boundary of the headbox slice, will deform the free surface of the liquid into the streaks that we see in Fig. 6. The upward and downward streams in the secondary flow form the crest and the trough of the streaks, respectively. The structure of the streaks that form at the slice depends directly on these secondary flows in combination with the nature of the headbox converging zone and the slice geometry. In some cases, there are two streaks generated for each column of tubes. Every pair of streaks corresponds to a column of tubes. Other types are when streaks form from jets delivered by staggered tubes, where a weak secondary streak exists next to a stronger primary streak. Our compu-

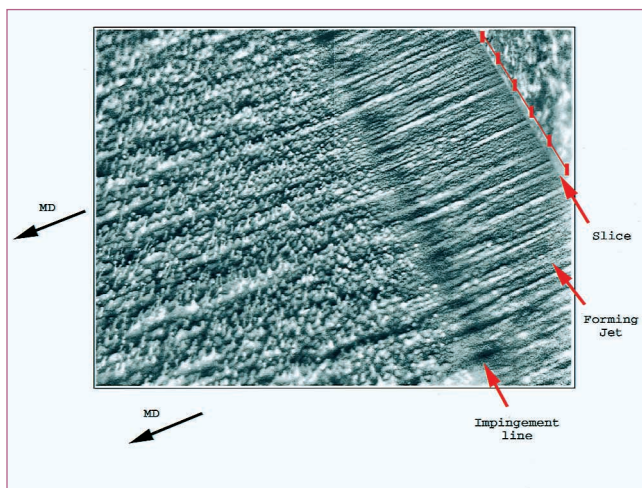
tational analysis of the interaction between the tube jets inside the headbox reveals the precise form of these secondary flows. More details about this will be presented in future publications.

Here we have discussed the origin of the streaks in the forming section. In the next section, we discuss the dynamics of the streaks.

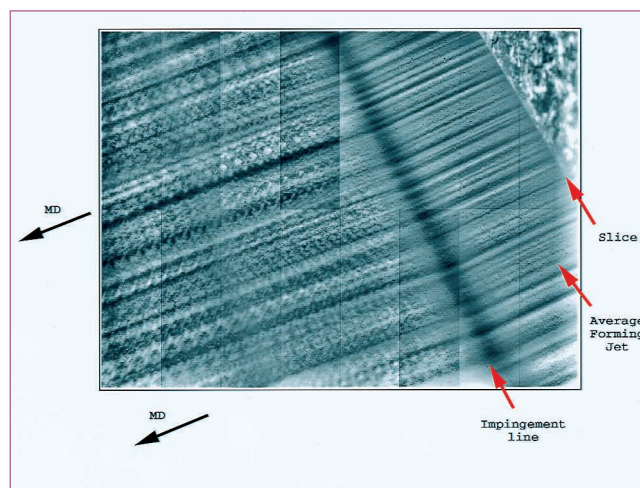
DYNAMICS OF THE STREAKS IN THE FORMING JET

Streaks on the forming table are caused by nonuniform or secondary flows in the headbox, the jet interaction with the wire, and the fluid dynamics of the free-surface flow on the forming table. With most forming sections, one can immediately see the narrow streaks that form near the slice. These streaks are 0.5–4 in. wide and correspond to the small-scale secondary flows emanating from the tube jets inside hydraulic headboxes or the wake of holes in the slice rectifier roll.

To analyze the dynamics of the streaks in the forming jet, we use a time-line projection imaging method. Events occurring in a fixed section of space are collected and assembled sequentially along a time line for analysis. This is shown in Fig. 8, where we have reconstructed the images of the forming jet over an



6. Time-frozen image of the forming jet, jet impingement region, and the stock activity after the impingement line. The red marks show a 1-in.-long scale (Machine speed = 3000 ft/min. Exposure time = 50 μ s).



7. Average of 500 images of the forming region shown in Fig. 4, covering a period of 0.5 seconds.

area of 0.6 x 6.2 in. at 1 in. from the slice over a period of 30 ms. This figure shows 30 sections outlined by red lines. The distance between adjacent red lines is 0.6 in. The blue lines show a 1-in.-square grid representing the length scale of the image. The images are taken at 1000 frames/second, and each frame has an exposure time of 50 μ s. Each 0.6-in. section, outlined by the red lines, represents the image at the same location of the forming jet (i.e., at 1 in. from the slice). Since the forming jet is moving on average at 3000 ft/min or 0.6 in./ms, the 0.6-in. sections move by exactly 0.6 in. in the machine direction each millisecond. The time line in Fig. 8 covers 30 images of the 0.6-in. sections from time 0 to time 30 ms, stacked in sequence from top to bottom. Time-line images up to several seconds can be constructed for analysis of the forming jet dynamics.

The physics and dynamics of the forming jet delivered by the headbox can be analyzed with these time-line images, as shown in Fig. 8. Considering that in this headbox, the spacing between the tubes in each row is about 1 in. and the tubes have a staggered pattern, and considering the average streak width in Figs. 7 and 8, one can state with some confidence that the streaks are due to the secondary flows from the jets delivered from individual tubes in the tube bank. In Fig. 8, we see the

effect of jets interacting from adjacent tubes. Careful analysis of these time-line images shows that the jets from adjacent tubes from two rows (i.e., ~0.5 in. apart in the cross direction) interact and compete with each other to leave a streak in the forming jet. Through this interaction, the streaks are deflected sideways. The interaction and subsequent deflection of the tube jets in the headbox result in sideways flapping motions of the streaks in the forming jet. The sideways motion of the streaks in the forming jet have a significant impact on the small-scale fiber orientation and formation in the sheet. In fact, we believe that the small-scale variations in fiber orientation are caused by the local dynamics of the streaks in the forming jet.

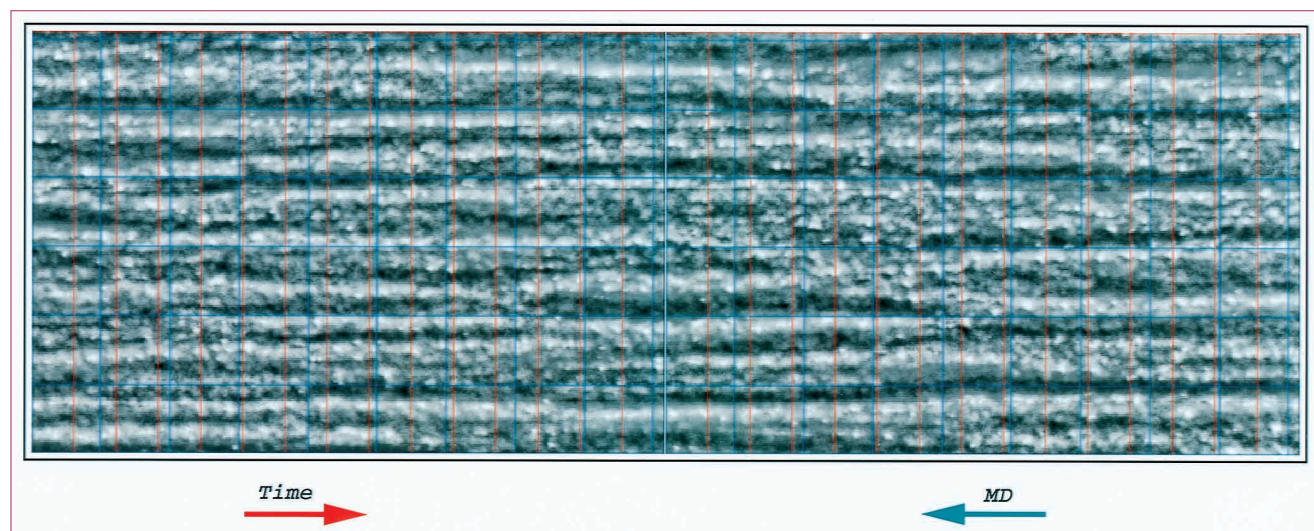
Although here we have only presented the images of the top of the forming section, we note that streaks should be viewed in terms of secondary flows throughout the forming jet. Similar streaks exist at the underside of the forming jet. Interaction of these streaks with the wire determines the structure of the sheet.

In the next section, we discuss the relation between the dynamics of the streaks in the forming section and the small-scale physical properties of the sheet.

THE IMPACT OF THE STREAK DYNAMICS ON SMALL-SCALE PHYSICAL PROPERTIES

We can approximate the variation in angle of the forming jet streaks with the machine direction from the time-line images in Fig. 8. If the distance from the tube outlet to the slice is 29 in. and the distance from the slice to the impingement line is 6 in., then for every 0.1 in. that a streak moves in the cross-machine direction of Fig. 8, the angle of the streak changes roughly by $\tan^{-1} (0.1/30) = 0.2$ degrees. Considering that fiber orientation is governed by the direction (or angle) of the velocity field relative to the machine direction in the forming layer, this variation in the local forming jet angle would result in significant fiber misalignment and fiber orientation nonuniformity over a small cross-direction length scale. The magnitude of the variation would depend on the forming jet angle and the rush/drag ratio (i.e., the shear rate in the forming layer). We predict that the length scale of the in-plane average fiber orientation variation in the first layer from the wire side would be on the order of the length scale of the streaks in the forming jet.

Jet/wire interaction and the evolution of the streaks along the forming section have a significant impact on the small-scale basis-weight and moisture profile. The mechanism and interaction between the layer on the forming section and the forma-



8. Time-line projection of the forming jet at 1 in. from the slice showing the dynamics of the streaks delivered from the headbox. The blue grid lines provide a 1-in.-square length scale. The 30 sections outlined by the red lines are the time sequence images of the forming jet stacked on top of each other over a 30-ms period imaged at 1000 frames/second with an exposure time of 50 μ s.

tion characteristics on the wire are currently under study.

To eliminate the nonuniformities in physical properties caused by the streaks in the forming section, we need to eliminate the small-scale secondary flows induced by the tube jets inside the headbox.

In the next section, we discuss a method for elimination of the streaks caused by the small-scale secondary flows from the tube jets in the headbox.

A METHOD TO ELIMINATE THE SECONDARY FLOWS GENERATED BY THE INTERACTION OF THE JETS FROM THE TUBES IN THE HEADBOX

To find a method to eliminate streaks in the forming jet, we need to first understand the mechanism of the generation of secondary flows inside the headbox. Large-scale computational simulation of the flow inside a

typical headbox has been carried out for this purpose. In this section, we provide a summary of the results. More details will be presented in the future (10).

The flow in a section of a typical headbox with tubes in a nonstaggered pattern is considered for this study. The flow at the inlet of the converging zone (i.e., the outlet of the tubes in the tube bank) is a typical fully developed turbulent profile, where the only nonzero velocity component is that normal to the boundary surface. The boundary conditions at the outlet of the nozzle (i.e., at the slice) are zero normal and tangential components of the stress tensor projected onto the outlet cross-sectional plane. The effect of the free surface at the outlet boundary will be discussed elsewhere (10).

The flow rate in the headbox is 0.0783 m³/m/s, and the average speed of the jet at the slice is 6 m/s. The contour plot of the speed and cross-direction velocity component at various cross sections of the converging zone of the headbox are shown in Fig. 9. The checkerboard pattern of + and - cross-direction velocity components show counterrotating secondary flows induced by the jets from the tubes. We believe that these sec-

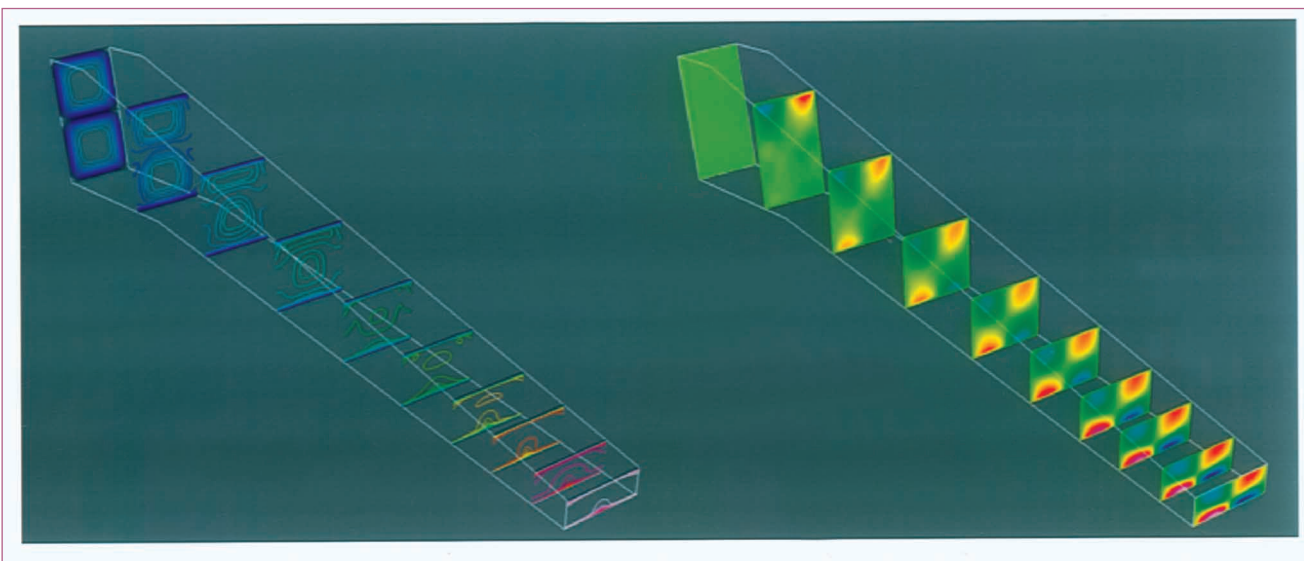
ondary vortices result in streaks at the forming jet. The contour plot of speed shows the top jet spreading around the bottom jet as the flow evolves through the headbox. This action generates the secondary flow pattern.

To better visualize the secondary flows, in Fig. 10 we show the trajectory of passive particles injected along a vertical line across the outlet of the tubes at the inlet of the converging zone at about 0.6 cm from the side of the tube column. The particle pathlines show how the secondary flow develops as a result of the jet-jet interaction.

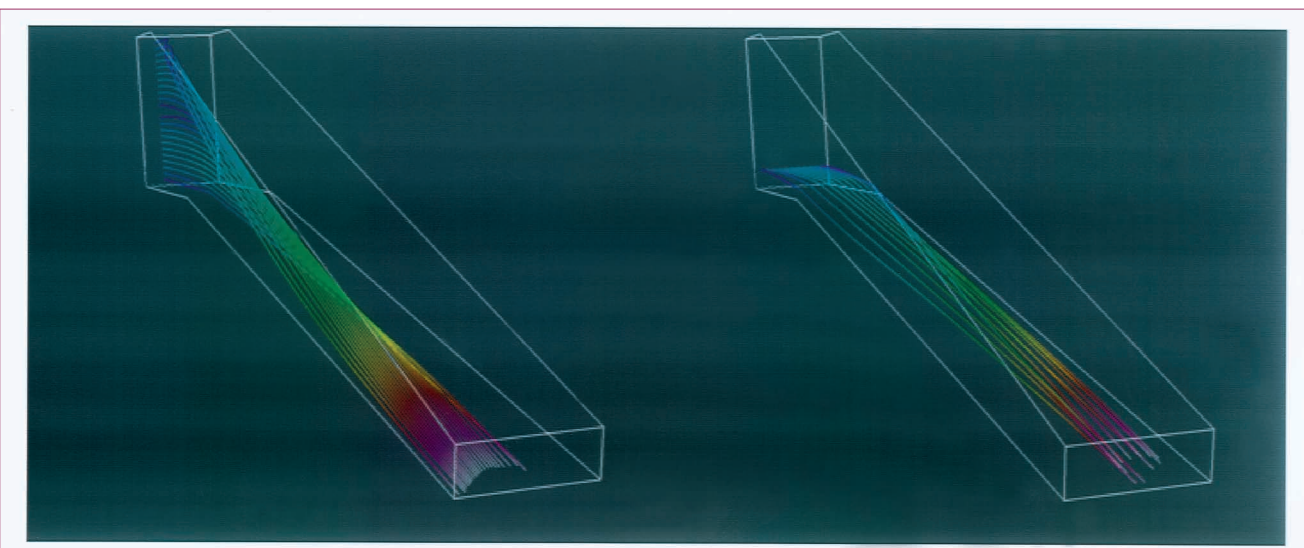
One method to eliminate the small-scale secondary flows previously discussed is to generate swirl in individual tubes in a controlled manner. The degree of swirl or the swirl number, S , is given by $S = Q/Xr$, where Q and X are the fluxes of the angular to axial momentum of the jet and r is the effective radius. If we set the swirl number to about 0.38, then the motion of the jets from the tubes will be considerably different. The jets rapidly interact and mix, as shown in Fig. 11. This figure shows the contour plot of the speed and cross-direction velocity component at various cross sections of the headbox.

KEYWORDS

Computation, defects, digital techniques, dynamics, flow, forming sections, high velocity, image analysis, jets, mechanics, simulation, streaking, tubes, variability, velocity.



9. Contour plot of the speed and cross-direction velocity component at various cross sections of the converging zone of the headbox. The checkerboard pattern of plus and minus cross-direction velocity components show counterrotating secondary flows induced by the jets from the tubes.



10. Trajectory of passive particles through the converging zone of the headbox, showing counterrotating secondary vortices at the slice.

The axial swirl can be generated by modifications to the tubes. We will present results of pilot trials using modified tubes in the headbox tube bank in future publications.

CONCLUSIONS

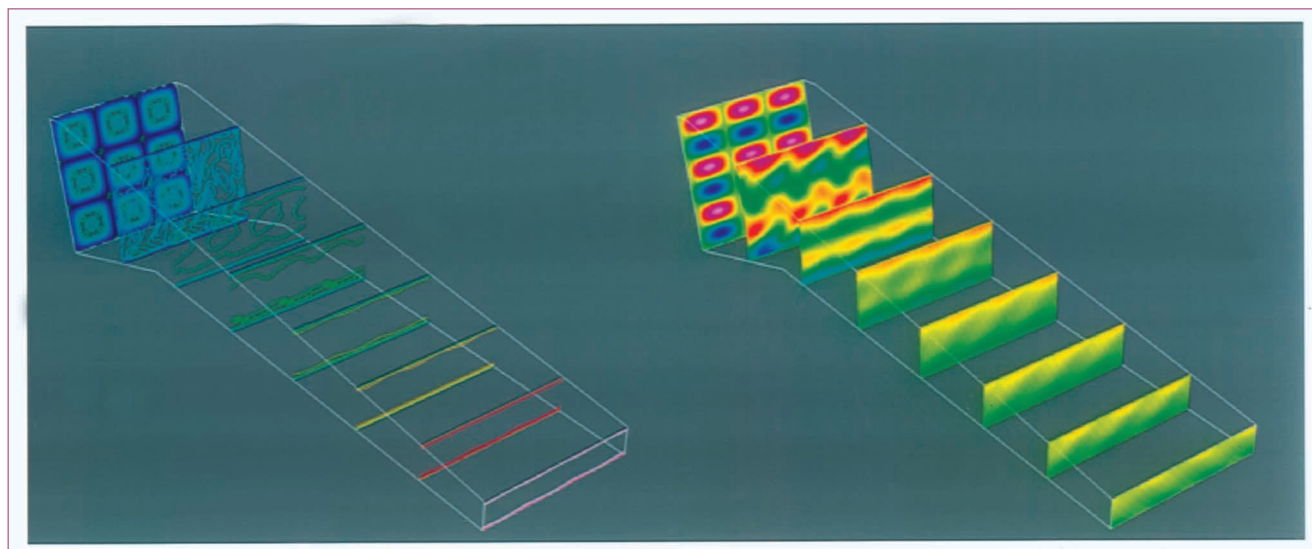
The origin of the layer nonuniformity in the forming section is the nonuniform free-surface jet delivered by the headbox onto the forming wire or into the gap former. Small-scale disturbances, secondary flows, and turbulence are generated by the headbox. The characteristics of the jet impingement on the wire defines the degree of amplification

of these disturbances. The role of the forming wire is to determine the relation between the disturbances and secondary flows in the headbox, and the fiber mat formation characteristics. Once the fiber mat has formed, i.e., after the dry line, the last two of the three fundamental physical properties are set in the sheet.

The headbox geometry and dimension, along with the flow rate and fluid properties, set the level of turbulence in the forming jet. The dimension, separation distance, and pattern or arrangement of the tubes in the tube bank, along with the converging angle of the headbox and the

slice lip, determine the magnitude, dimension, and dynamics of the small-scale secondary flows and, consequently, the characteristics of the streaks in the free-surface forming jet delivered at the slice.

The jet impingement on the forming board results in the amplification of the disturbances, where the degree of amplification is proportional to the impingement angle. That is, the larger the impingement angle, the larger the amplification of the disturbances. This is due to an acceleration-induced instability that is well understood.



11. Contour plot of the speed and cross-direction velocity component at various cross sections of the converging zone of the headbox, with axial swirl generated by the tubes in the tube bank. The checkerboard pattern of the cross-direction velocity components disappears, showing a uniform jet at the slice.

As the streaks form in the forming jet, amplify upon impingement, and evolve along the forming wire, there is a characteristic growth and decay rate associated with the streaks. The growth and decay rates determine the rate of growth and decay of a streak on the forming wire. Analysis of the streak formation and decay (8) shows that these rate factors depend on the turbulence level of the flow, the average thickness of the layer, and the width (or wavelength) of the streaks. In general, the very narrow streaks grow and decay very rapidly. The growth rate of the wide streaks is relatively small. As the disturbances and streaks evolve through the forming section, the narrowest streaks form and decay not far from the forming

board. Gradually wider streaks form down the forming section. Depending on the wire speed and the growth and decay rates, streaks with a critical width dominate the surface characteristic of the forming layer at the dry line.

The interaction and dynamics of the tube jets inside the headbox result in small-scale cross-direction oscillation or flapping of the streaks in the forming jet. This cross-direction motion results in small-scale variations in fiber orientation and fiber network in the sheet.

The most effective mechanism to eliminate this fundamental defect in paper forming is to eliminate the small-scale secondary flows induced by the tube jets. This can be achieved by modifications to the tubes in the

tube bank for generation of swirl or axial vorticity in individual jets. **TJ**

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