

# Fundamental study of screening hydraulics

## Part 1: Flow patterns at the feed-side surface of screen baskets; mechanism of fiber-mat formation and remixing

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**ABSTRACT:** Flow patterns at the feed-side surface of smooth and contoured screen baskets were studied. For contoured baskets, throughput and the degree of fiber stapling depended strongly on the relative position of the contour, the size of the opening, the eddy size, and the intensity in the wake zone. The way that fibers migrate toward the screen openings is very sensitive to the height of the contours. Examination of these hydraulic and physical characteristics helped clarify the working mechanism inside a screen and facilitated screen design and basket selection for different applications with different furnishes. Part 2 of this study examines the trajectory of fibers toward openings on various types of screen baskets. Part 3 presents a model for calculating the effective open area inside a screen basket when the screen is running.

**KEYWORDS:** Baskets, containers, fiber mats, fibers, flow, fluid mechanics, formation, fractionation, hydraulics, mechanics, mixing, screening, separation, unit operations.

The pulp and paper industry has used pressurized screening to remove pulp contaminants or to fractionate stock for several decades. A wide variety of screen baskets and rotors have been developed for different applications and furnishes. Despite this diversity, the factors

affecting screening efficiency and throughput can be divided into three categories:

1. Screen parameters (type of basket, type of rotor)
2. Operating parameters (operating consistency, rotation speed)

3. Stock parameters (fiber type, freeness, types of contaminants).

Most of these parameters have been widely investigated (1-11). However, there is little published research concerning the fundamental mechanisms governing flow characteristics and fiber motion around the openings on a screen basket.

Riese *et al.* (12) studied stiff fibers approaching a screen plate at a normal angle of incidence. Their results provided some insights regarding fiber retention rate. However, the experimental conditions used in the study were much different from those inside a pressure screen.

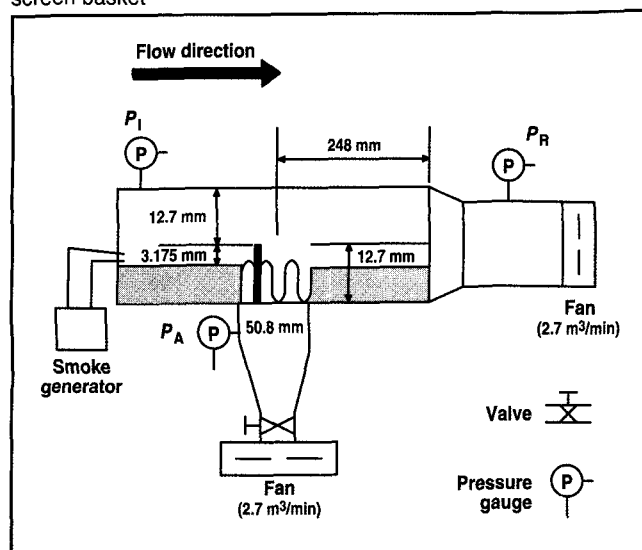
Thomas and Cornelius (13) studied flow patterns around a suction slot on a smooth basket under laminar conditions. The fluid used in their experiments was water.

Oosthuizen *et al.* (14) investigated water and fiber flow down a channel in the vicinity of a wall slot (1-mm wide) under laminar flow conditions. Fiber motion was studied by injecting dyed fibers into the flow. They found that the 1-mm slot provided a highly curved flow field that is potentially usable for measuring fiber flexibility. Their study of fiber motion also indicated that fibers did not separate from the curved streamline flows near the slot.

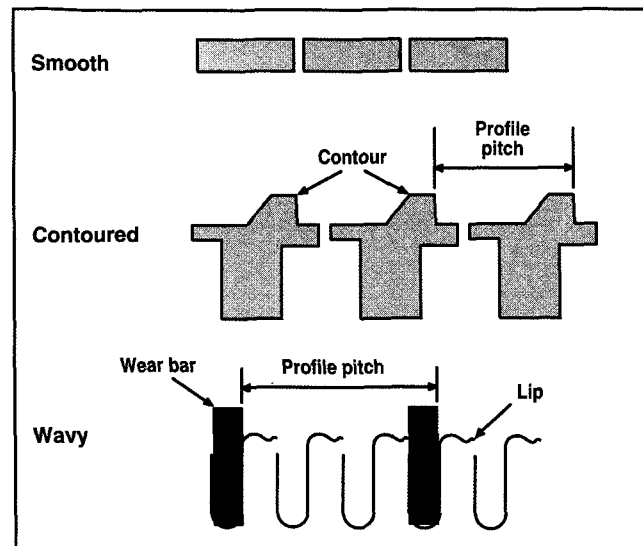
Gooding and Kerekes (15) studied fiber trajectories in the entry

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1. Apparatus for studying flow patterns of smoke at the surface of a screen basket



2. Three slotted-screen basket designs



zone of a single slot (0.5-mm wide) in a 19-mm square channel. The slot velocities were 3.1 m/s, 3.2 m/s, and 7.1 m/s (i.e., in the turbulent regime), and two types of nylon fibers were used. Both types of fibers were of the same length (3.1 mm), but they differed in terms of diameter and stiffness (0.043 mm and  $10^{-10}$  Nm<sup>2</sup> vs. 0.230 mm and  $10^{-5}$  Nm<sup>2</sup>). High slot velocities substantially increased fiber passage through the slot. The study also showed that screening took place by two mechanisms: a "wall effect" that lowered the concentration of stiff shive-like fibers in the flow entering the slot, and a "turning effect" that caused stiff shive-like fibers to rotate instead of bending as they turned into the slot. These rotating fibers tended to be swept away from the slot by the mainstream flow, whereas the more flexible pulp-like fibers tended to bend and enter the slot.

Halonon *et al.* simulated flow patterns near a slot on a conventional and a contoured screen basket (16). They found that at the same conditions, the average slot velocity for the contoured basket was about 50% higher than for the conventional basket. They also reported that the capacity of the slotted contoured basket was 50–300% greater than the con-

ventional basket. These findings—that higher slot velocity implies greater capacity—agreed with those of Gooding and Kerekes (15). However, Gooding also reports that higher slot velocities increase the probability that a shive will be accepted (17).

All of these studies used a single slot or artificial fibers. The present work attempted to simulate the conditions inside a pressure screen by using coupons of commercial baskets and three different furnishes (old corrugated cartons, old newsprint, bleached softwood kraft). The aim of the present work was to gain insights into the screening mechanism by studying flow patterns around commercial screen baskets, investigating the formation and remixing of fiber mats on screen surfaces, and examining the way fibers approach screen openings.

## Experimental work

Experimental work was divided into three stages. The first stage focused on flow patterns at the feed side of commercial screen baskets. The second stage examined the mechanisms of fiber-mat formation and remixing. Results for both stages are reported here in part 1. The third stage

investigated the trajectory of fibers approaching openings on a screen basket, and these results will be presented in part 2, scheduled for publication in September. Part 3, also scheduled for publication in September, presents a model for calculating the percent open area inside a screen basket when the screen is running.

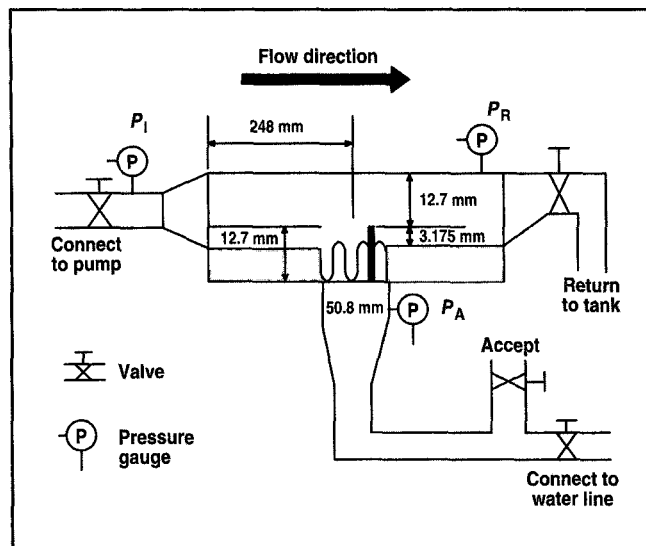
## Stage 1—Flow patterns (smoke)

The apparatus used to study flow patterns during pressurized screening is shown in Fig. 1. The variables  $P_I$ ,  $P_R$ , and  $P_A$  represent pressure at the inlet, reject, and accept sides of the model, respectively. The apparatus was constructed of transparent materials, which made it possible to observe flow patterns.

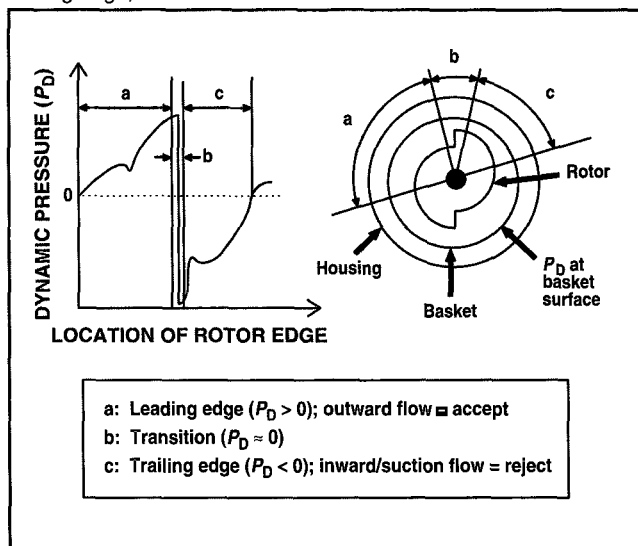
Three different types of slotted-basket configurations (smooth, contoured, and wavy) were studied, and these are illustrated in Fig. 2. A perforated wavy basket—the only one available on the market (Belwave™, Beloit Corp., WI)—also was included in the study.

The flow fields around the basket surfaces were studied in a simplified way. A single 0.4-mm slot was used for both the smooth and contoured baskets. In the case of the two wavy baskets (slotted or perforated openings), the presence of wear bars at

3. Apparatus for studying fiber-mat formation and remixing at the feed side of a screen basket



4. Definition of three terms describing rotor position: leading edge, trailing edge, and transition



intervals of 25.4 mm made it necessary to use a screen model spanning three undulations, as illustrated in Fig. 2. Slot width for the slotted wavy model was 0.254 mm; hole diameter for the perforated wavy model was 1.143 mm.

Screen models were mounted in the middle of a rectangular channel (86 mm x 12.7 mm) in the apparatus illustrated in Fig. 1. Instead of a pulp slurry, smoke was used to enhance visualization.

A smoke generator was placed on the left-hand side of the flow channel. Two fans were mounted to the apparatus: one at the right end of the model and the other located beneath the model. Both fans had a capacity of 2.7 m<sup>3</sup>/min and were mounted with the suction side toward the model. The fan mounted at the right end of the channel, which drove the smoke from left to right, was always on. The fan positioned beneath the flow model was turned on and off to simulate the pulse of a rotor. When the fan was on, a portion of smoke was removed from the bottom of the apparatus, simulating the flow of pulp slurry through the screen basket. When the bottom fan was turned off, the difference in pressure caused air to be sucked through the basket. This was analogous to

the suction flow created as the trailing edge of a rotor passes by.

The gap between the top wall of the apparatus and the screen-basket model was kept at a constant level of 12.7 mm. This corresponds to the minimum gap used in the Beloit S screen. The flow rate was constant for the different basket models. Thus it is reasonable to assume that Reynolds number was the same for the different basket models. (Reynolds number is the ratio of inertial and viscous forces and is defined as  $UD_H/\nu$ , where  $U$  is the mean velocity,  $D_H$  is the hydraulic diameter or characteristic length, and  $\nu$  is the fluid viscosity.) Because the flow conditions remained constant, a fair comparison among the observed flow phenomena for different basket models could be made.

### Stage 2—Fiber-mat formation and remixing (pulp slurry)

In the second stage of the experiment, the smoke was replaced by a pulp slurry, and the fans were replaced by pumps. Figure 3 depicts the apparatus used to model pulp flow. The apparatus resembles the one illustrated in Fig. 1. By controlling the pressure beneath the screen model, either pulp slurry flows out of

the apparatus to the accept side (when  $P_A < P_I$ ) or water flows into the apparatus from the accept side (when  $P_A > P_I$ ). The flow rate was varied from 3790 cm<sup>3</sup>/s to 8843 cm<sup>3</sup>/s during the experiment.

Three different types of pulps were used in the second stage of experiments: old corrugated containers, old newsprint, and bleached softwood kraft. Pulp consistency was varied from 0.1% to about 2%. When the consistency approached 2%, light could not penetrate the flow model, and no results could be recorded. Most flow fields were recorded at approximately 0.5% consistency with a NAC HSV-400 high-speed video camera with a recording speed of 200–400 frames per second.

### Flow patterns (smoke)

#### Slotted and perforated baskets

The wake length, the velocity profile inside the channel, and vortices were clearly observed during the experiments with smoke. Streamline flows were extracted from videos of the three slotted baskets (smooth, contoured, wavy) at two flow conditions:

1. Trailing edge of the rotor passing the screen, creating negative pres-

## Screening

sure and suction flow to the reject side of the screen

2. Leading edge of the rotor passing the screen, creating positive pressure and outward flow to the accept side of the screen.

**Figure 4** illustrates the effect of the rotor's position on flow through a pressure screen.

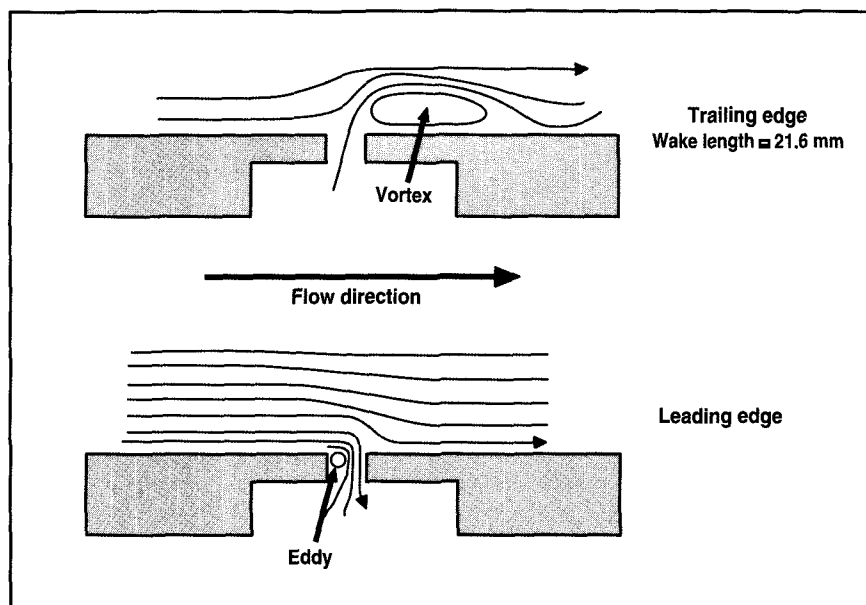
**Figures 5–7** show the streamline flows extracted from videos of the three slotted baskets (smooth, contoured, wavy) at the two flow conditions. The streamline flow observed around the slot on a smooth surface (Fig. 5) is the same as that reported by Thomas *et al.* (13) and Oosthuizen *et al.* (14). A small eddy was observed at the upstream edge of the slot entrance. This eddy was due to flow separation that occurred at the entrance.

Wake length—the distance from flow separation to reattachment of flow on the surface of the screen model—is a function of suction flow. During the suction-flow period, average wake length for the slotted smooth, slotted contoured, slotted wavy, and perforated wavy baskets was 21.59 mm, 19.05 mm, 25.40 mm, and 12.7 mm, respectively.

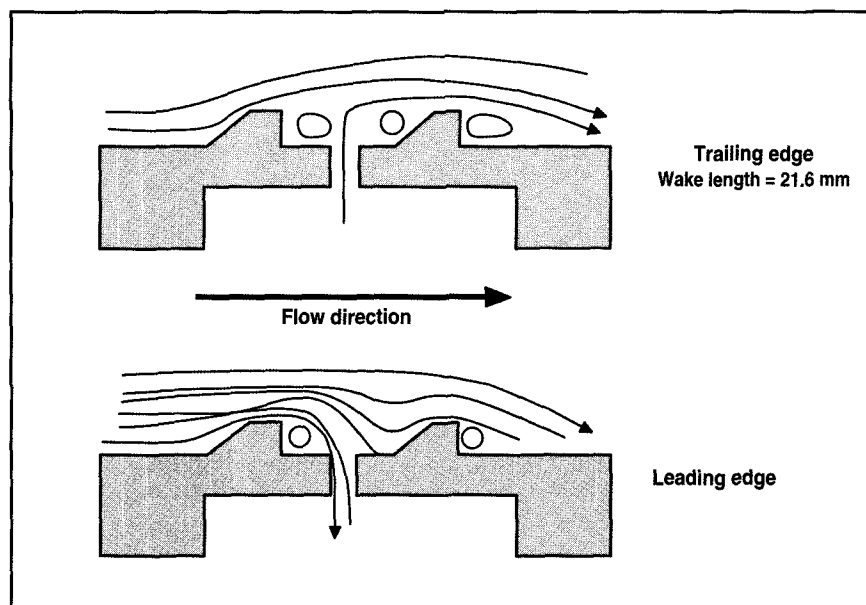
Flow separation on the screen surface was observed for the contoured (slotted) and wavy basket (slotted or perforated) models. This flow separation is caused by the introduction of a contour (contoured screen) or a wear bar (wavy screens). No separation was observed on the surface of the smooth (slotted) model when flow goes from feed side to accept side.

Vortices were seen before and after both the contour of the contoured basket and the wear bar of the wavy basket. The wake effect created a local pressure difference before and after the wear bar of the wavy model. Thus, a clear smoke flow was observed underneath the corrugated model during transition from outward flow to inward flow. The smoke went out the slot before the wear bar and came back into the flow chan-

5. Streamline flow for slotted smooth basket



6. Streamline flow for slotted contoured basket

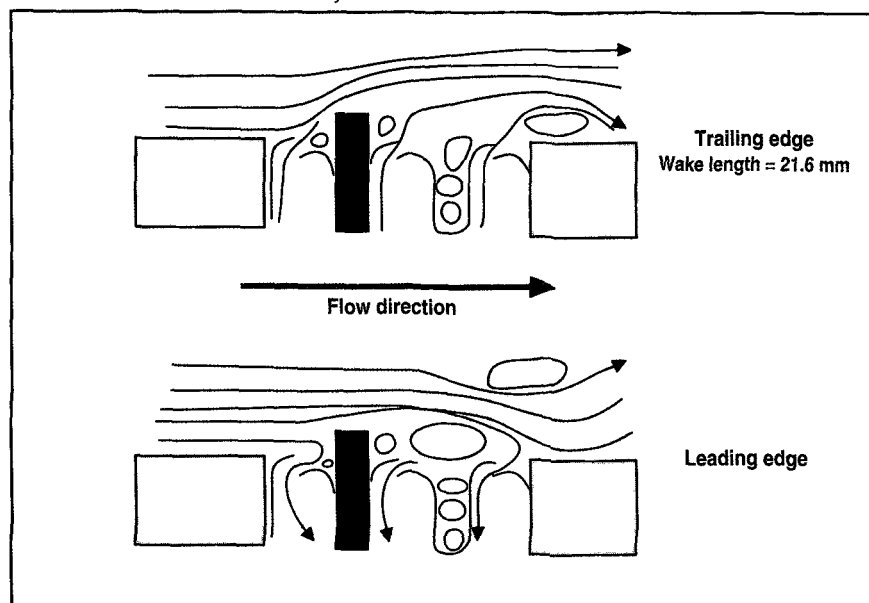


nel again from the slot(s) after the wear bar.

The vortex observed after the wear bar of the wavy model (Fig. 7) was much bigger than that of the contoured model (Fig. 6). This was mainly because the wavy model had a higher profile (because of the wear bar) than the contoured model. The wear bar used in the wavy basket is 3.175 mm above the undulations, which is the standard configuration

of the commercial wavy basket. There was no vortex observed on the surface of the smooth basket, since there was no flow separation.

The streamline of smoke was straight while it went through the slots for both the contoured and smooth basket models. That of the contoured basket oscillated back and forth, but the amplitude was very small. The situation observed for the wavy model was different. The flow



went through the slot of the wavy basket in a curved path and was in the reverse direction with respect to the main flow. This was because the plane of open area of the wavy material is not like that of the contoured and smooth baskets, which are in a plane perpendicular to the radial direction. Instead, the plane of open area of the wavy basket is in a plane parallel to the radial direction, as seen in Fig. 8. Thus, it was obvious that the flow through the slot was coming from the vortex instead of flow reattachment. Consequently, the streamline through the open area was a curve instead of a straight line.

#### Wavy baskets—difference in flow patterns for slotted and perforated screens

The flow pattern for the perforated wavy basket was completely different from its slotted counterpart. The recirculation characteristics during transition were not found in the perforated material. This might be due to significantly higher open area in the perforated material. Thus, velocity above the screening zone was not as high as for the slotted material, and the pressure difference be-

fore and after the wear bar was reduced. So, no recirculation occurred during the flow transition from outward to inward.

The wake length observed for the perforated material was only about half of that observed for the slotted material. The ratio of wake length to wear-bar distance was about 0.5:1.

Part of the accept flow was passing through the perforated wavy basket by flow reattachment, and the rest of the accept flow was driven by the vortex. Therefore, the outward flow mechanism of the perforated basket was different from that of the slotted wavy basket, whose accept flow was completely due to vortices. In the perforated wavy basket, the second undulation of the three undulations between the wear bars had the highest flow rate. This is because flow reattachment occurred in that particular position.

#### Summary of flow-pattern findings

The investigation of flow patterns revealed the following:

1. Flow separation occurs on the contoured and wavy basket screens. Apparently, the separation is due to the introduction of a profile or wear bar, since no sepa-

ration was observed on the surface of the smooth screen when flow goes from feed side to accept side.

2. The ratio between wake length and the profile pitch is close to 1 for the slotted wavy basket, 0.5 for the perforated wavy basket, and 4–5 for the contoured basket.
3. Outward flow (accept flow) for the smooth basket is caused by local pressure difference only. Outward flow for the contoured basket is mainly from reattachment of the flow stream. Outward flow for the slotted wavy basket is from the vortices rather than flow reattachment. This is because the openings of the slotted wavy basket are on the back of the wear bars and because the plane of the open area is parallel to the radial direction, instead of perpendicular to the radial direction (as in cases of the smooth and contoured models). Outward flow for the perforated wavy model is from both vortices and flow reattachment.

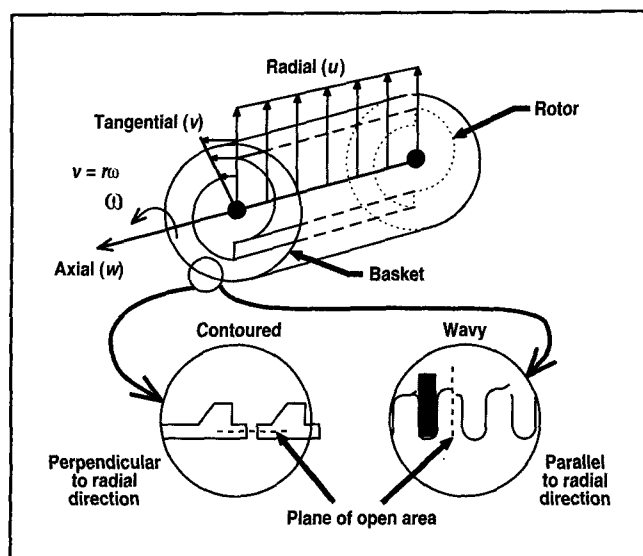
#### Fiber-mat formation and remixing (pulp slurry)

##### Basket models

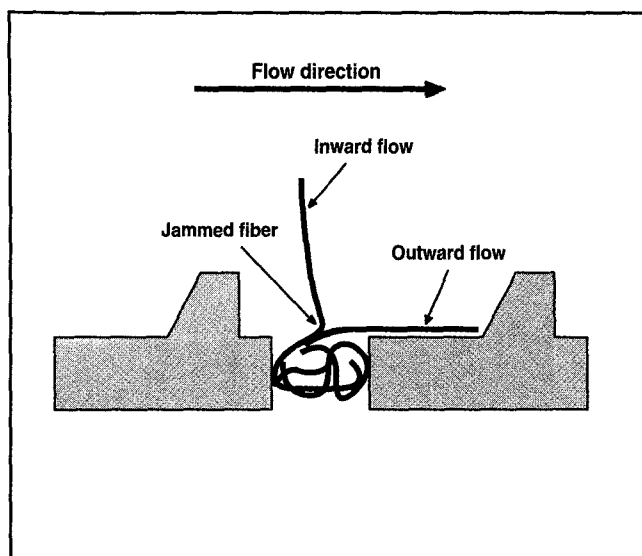
In the second experimental stage, an 86-mm x 50-mm basket coupon was used instead of a single slot or three slots. Three different types of pulp were used: old corrugated containers, old newsprint, and bleached softwood kraft. Four different basket models were investigated: slotted (0.254 mm in width) and perforated (1.143 mm in diameter) wavy baskets, perforated (drilled) smooth basket (2 mm in diameter), and slotted contoured basket (0.254 mm in width).

**Slotted wavy basket.** There was no clear fiber-mat formation observed in the slotted wavy basket experiments, regardless of the pulp that was used. It was believed that vortices between the wear bars and undulations strongly reduced the

8. Definitions of velocity direction (radial and tangential) and plane of open area



9. Motion of jammed fiber at inward and outward flow conditions on a slotted contoured basket



chance for a fiber to reside on the edge of the slot. Also slot spacing (7.5 mm) is longer than the average length of most fibers, so no stapling can occur.

**Perforated wavy basket.** Occasionally, fibers and/or flocs stapled or hung on the openings of the perforated wavy basket, but these were always freed and remained in the feed side during the suction flow. However, fibers or flocs that stuck in the openings usually needed several pulsations to set them free either into or out of the basket.

**Slotted contoured basket.** Some fibers or contaminants became caught in the slots of the contoured basket. The motion of these captured fibers or contaminants was neither in nor out of the basket, nor oscillating. Instead, the fibers responded to the pulsating flow conditions by standing up or lying down on the basket surface. This phenomenon is illustrated in **Fig. 9**. Meanwhile, fibers, flocs, and contaminants were residing around the open areas during simulation of outward flow. When a fiber or floc or contaminant landed on the edge of an opening, it started to grow rapidly by capturing other fibers/contaminants via the interaction of fibers. When the height of

the fiber/contaminant pile grew to about 2 mm, it was swept away by the main flow stream. During simulation of suction flow, all the piles or mats were broken or remixed.

**Perforated smooth basket.** Fibers did not stick in the openings of the perforated (drilled) smooth basket, in contrast to the situation with the slotted wavy and contoured basket models. Only a few big pieces of flakes/contaminants were temporarily caught in the holes. This was mainly because the large opening prevented fibers or contaminants from jamming or sticking.

However, formation of a fiber ball or pile around a seed (fiber, floc, flake, or contaminant) resting on an open area was also observed with the perforated smooth basket screen. The maximum thickness of the mat was about 3 mm. When the fiber ball or pile accumulated to this critical height, it was dragged away by the main stream. This pile of fibers and contaminants was always blown apart or remixed during suction flow.

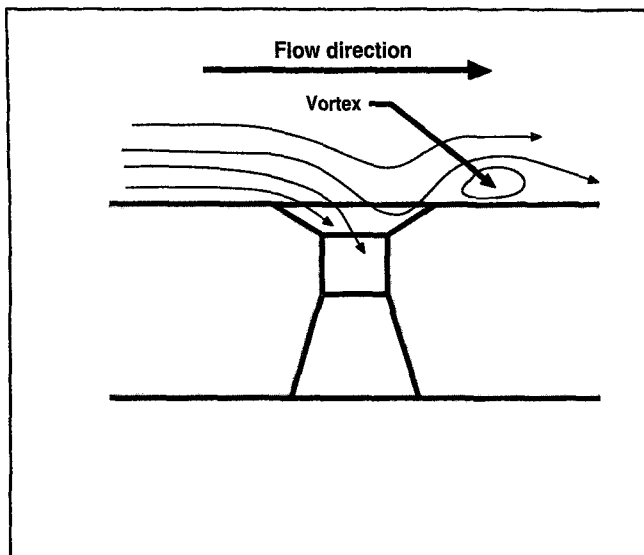
The slope of the drilled openings of the perforated smooth basket and the streamlines around the slope are shown in **Fig. 10**. It can be seen that the slope of the drilled hole served like a profile of the contoured bas-

ket. The drilled hole caused flow separation and created a small wake zone.

## Mechanism of fiber-mat formation and remixing

The experimental observations showed that the "fiber mat" was really a collection of fibers, contaminants, flocs, and flakes building up randomly around the screen openings. A seeding material was needed to initiate buildup of these materials. The seed could be fiber, floc, flake, contaminant, or a combination of these materials. Once a seed stapled or hung on the edge of an opening, additional material quickly accumulated around the seed to form an individual pile. The accumulation occurred via the interaction of fibers, and a mat could be formed if the piles were close to each other. The process of mat building was very fast. The time needed to build a fiber/contaminant pile to its critical height was within several thousandths of a second, with the precise time depending on furnish consistency and type.

The maximum thickness of this fiber mat was about 2-3 mm, depending on the basket style and furnish type. Once the mat exceeded



this maximum or critical thickness, it was broken and carried downstream by the main flow. However, it must be pointed out that the experiments were performed in a rectangular channel with a height of 12.7 mm. The pressure inside the channel was constant. In a real situation, positive pressure is generated by the pump and by the rotor. If the positive pressure is too high, the negative pulse too low, or the frequency of the rotor too low, it is highly possible that the mat will be jammed into the openings, leading to plugging of the basket.

A fiber/contaminant mat was clearly observed in the models for the slotted contoured basket, the drilled perforated smooth basket, and the perforated wavy basket. However, no mat was observed in the model for the slotted wavy basket. Apparently, the wide slot spacing and the strong vortices formed between the wear bars during undulations prevented flocs, flakes, or contaminants from residing on the openings.

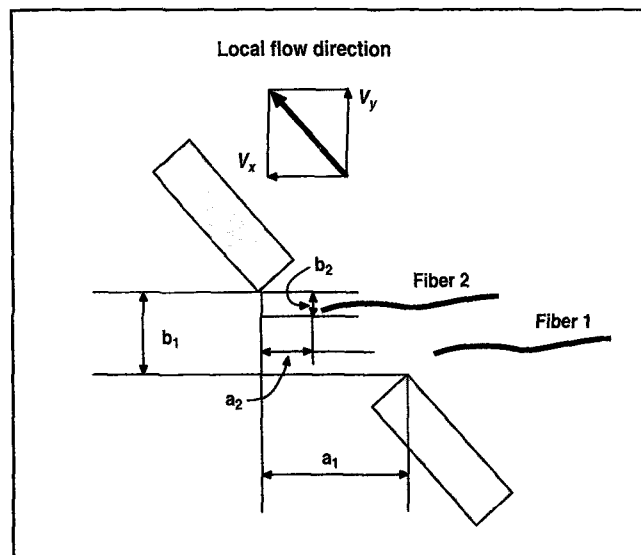
### Stapling mechanism

Stapling was observed in the slotted contoured, perforated smooth, and perforated wavy baskets. While the

stapling phenomenon is a well-known event in the screening process, it is not completely understood. Therefore, it is necessary to take some time to resolve how fiber is stapled on the edges of screen openings.

Figure 11 shows an enlarged view of an opening and two fibers approaching the opening. Each fiber approaches an opening at a different position and at a different angle. In this case, Fiber 2 moves toward a hole at the top edge of the opening, while Fiber 1 approaches the opening at the bottom edge. The projected width and height that a fiber must travel to pass completely through an opening are different, depending on the initial position of the fiber. For example, for Fiber 1, the horizontal and vertical distances available are  $a_1$  and  $b_1$ . However, for Fiber 2, the horizontal and vertical distances available are  $a_2$  and  $b_2$ , much smaller than the distances for Fiber 1.

The projected width and height are denoted as  $W_p$  and  $H_p$ . The horizontal ( $x$ ) and vertical ( $y$ ) velocities of the local flow are  $V_x$  and  $V_y$ . For simplification, the axial velocity is not taken into consideration here. However, in a real situation, the  $z$ -direction velocity is the axial veloc-



ity. This velocity is a function of flow rate and position along the axial direction, and it is normally smaller than the tangential and radial velocities. The period of time,  $t$ , needed for a fiber of length  $L$  to shift itself completely through the projected width can be defined as

$$t = (W_p + L)/V_x \quad (1)$$

Thus, in order to have a fiber of length  $L$  pass completely through the opening, the following condition must be satisfied:

$$t V_y \leq H_p \quad (2)$$

If  $t V_y$  is greater than  $H_p$ , one of the following situations will occur:

1. If the fiber length inside the basket is shorter than the distance between openings, the fiber hangs in the edge of the opening.
2. If the fiber length inside the basket is larger than the distance between openings, both ends of a fiber will hang on the edges of two different openings. In other words, the fiber is stapled.

(This hypothetical supposition is a special case applying to a straight fiber approaching the opening at a zero-degree angle. This is not nor-

## Screening

mally the case, and a fiber might approach an opening in a curved shape or in the form of a floc, depending on velocity and consistency. All kinds of possibilities could occur, but the calculation will be similar.)

### Summary—mechanism of fiber-mat formation and remixing

The study revealed several important phenomena affecting the mechanism of fiber-mat formation and remixing:

1. Fiber mats did not form without seeding materials near the screen openings. The seeds were flocs/flakes or large contaminants occupying the edge of an opening.
2. A flow vortex impedes formation of fiber mats by dislodging big flocs, flakes, or contaminants from the edge of a screen opening.
3. Suction flow (remixing) can clear flocs/flakes or large particles that are resting on the edge of a screen opening. Remixing is less effective in eliminating fibers or contaminants that are jammed into screen openings. The presence of jammed fibers or contaminants can result in stringing because of the interaction of fibers.

### Conclusion

This work provides detailed information about flow patterns around the surface and the opening of different types of screen baskets. Relevant differences among the various baskets are described, and the effects of these differences on throughput and efficiency are examined.

This report also describes how mats containing fiber and contaminants can form on the surfaces of different baskets and how these mats are remixed and rediluted for further treatment.

The information presented here helps explain some well-known phenomena in the screening process, such as stapling and the effect of

opening location on screen throughput. The study results can provide guidance in selecting screen baskets for different applications and furnishes. □

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