Factors controlling the passage of fibers through slots

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ABSTRACT

The passage of fibers through apertures is the essential action of pulp screening. Screen capacity, contaminant removal efficiency, reject thickening, and other important parameters of screen operation can be linked to fiber passage by mathematical models. To obtain a better understanding of fiber passage and improve screen performance, tests were made using a flow channel. These tests revealed that fiber passage increases dramatically with increased slot velocity. Passage also increased with increased slot width, increased fiber flexibility, reduced fiber length, and reduced upstream velocity. The ability of screens to segregate one type of fiber from another was found to be greatest at low slot velocities.

Application:

A laboratory study showing how different operating parameters affect pulp-screening efficiency.

PULP SCREENS ARE AN EFFECTIVE and widespread means of removing oversize contaminants from pulp. Screens play an important role in meeting the high quality and runability standards of papermakers by eliminating dirt, cleaning recycled furnishes with high contaminant loads, and enhancing pulp quality by fractionating one type of fiber from another. Further improvement of screen performance calls for a better understanding of fundamental screening mechanisms.

In a general sense, the operation of a pulp screen is straightforward. It receives a feed stream of pulp and separates it into an accept stream of cleaned pulp and a reject stream, where contaminants are concentrated. Separation is effected by a screen plate within the pulp screen, which has apertures that allow pulp fibers to pass while blocking shives, plastic, and other oversize contaminants.

Closer study reveals that the screening action is not quite so simple. Pulp fibers do not pass through the apertures without restriction, which is shown by the drop in consistency from the feed to the accept streams. Moreover, the removal of shives and coarse fiber is incomplete. A comparison of the size of the fibers, contaminants, and apertures does not explain these effects.

This paper attempts to explainthe mechanism of screening by presenting measurements of fiber passage through a flow channel that simulated key aspects of what happens in a pulp screen.

BACKGROUND

Performance equations for fine screens in pulp and paper manufacture can be directly linked to the separation ratio, α, of individual apertures *(1)*. This ratio and the screen's mass reject ratio, R_M, determine the overall screen efficiency, E. Reject ratio is defined here as the fraction of the pulp in the feed flow that leaves in the reject flow, while E is the fraction of the contaminants that leaves in the reject flow. Thus an ideal screen would provide complete contaminant removal ($E = 1$) with no loss of good pulp ($R_M = 0$).

The same study *(1)* showed that α is equal to the screening quotient, Q, in the widely used Nelson equation *(2)* relating E and R_M

$$E = \frac{R_M}{1 - \alpha + \alpha R_M} \tag{1}$$

This equation is based on the case of fully mixed flow in a pulp screen. In contrast, a power-law equation applies for the case of a plug-flow model

$$E = R_M^{1-\alpha} \tag{2}$$

In the derivation of these performance equations, the value of α was shown to depend on the passage ratio of the desirable (P_X) and undesirable (P_Y) components through the apertures. Passage ratio is defined as the ratio of the concentration of a component in the flow through a slot, C_S, to the concentration of this component in the flow just upstream of the slot, C_U.

$$P = \frac{C_S}{C_U} \tag{3}$$

The passage ratios of the desirable and undesirable components are defined by the respective concentrations of those components.

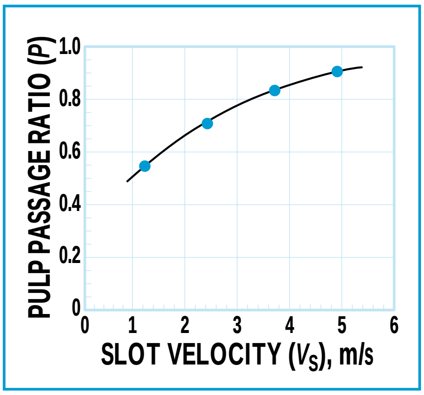
$$P_X = \frac{C_{S,X}}{C_{U,X}} \tag{4a}$$

$$P_Y = \frac{C_{S,Y}}{C_{U,Y}} \tag{4b}$$

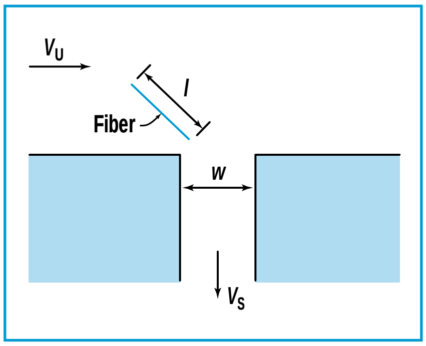
The relationship between α, P_X, and P_Y was shown to be:

$$\alpha = 1 - \frac{P_Y}{P_X} \tag{5}$$

Combining Eq. 5 with either Eq. 1 or 2 shows how the performance of an industrial pulp screen, E, is linked to what happens at the individual apertures. The link is through the passage ratio.



***1. Effect of slot velocity on passage ratio, inferred from measurements of reject thickening in a pilot plant screen* (3)**



2. Some key parameters of flow through a single slot

Analysis of the reject thickening factor, T, provides another example of how passage ratio is related to the performance of industrial pulp screens *(3)*. The reject thickening factor is defined as the consistency of the reject pulp divided by the consistency of the feed pulp. One seeks to minimize T because high reject consistencies can lead to plugging in the reject line. High reject consistency will also reduce the production tonnage because of the associated decrease in accept consistency.

Using the plug-flow model, it was shown *(3)* that

$$T = R_V^{P_P-1} \quad (6)$$

where P_P is the passage ratio of pulp and R_V is the volumetric reject ratio, i.e., the volumetric reject flow divided by the feed flow. The relationship of T to R_V is important, since R_V is the principal operating variable for industrial pulp screens.

Pilot plant measurements of T confirmed the form of Eq. 6 and, hence, the validity of the plug-flow model for the particular pulp type, consistency, and screen hardware used in the test. Values of P_P over a range of slot velocities, V_S, are shown in **Fig. 1**. Passage ratio is equal to 0.7 at a typical V_S of 2.5 m/s, and P_P increases exponentially toward a value of 1.0 with increasing V_S.

Passage ratio is clearly of great importance to pulp screen operation. The factors affecting P have been examined in fundamental studies of fiber passage through slots *(4–8)*. In a study carried out using high speed films of fiber motion near a single slot *(4)*, passage ratio was found to be governed by two factors: a "wall effect" and a "turning effect." The wall effect was caused by a concentration gradient of fibers near the wall (i.e., the screen plate). The turning effect represented the influence of the slot entry on fiber passage. The study found that both effects were diminished (i.e., P increased toward a value of 1.0) with increased slot velocity or fiber flexibility. In subsequent work *(5)*, the turning effect was postulated to be made up of three components—fiber penetration, rotation, and bending. Detailed analysis of fiber motion and its effect on passage has been conducted by Olson *(6)*.

Although these studies have identified and analyzed some of the factors that affect passage ratio, its importance calls for a greater understanding of how it is affected by the flow conditions at the slot entry and the properties of the fibers.

EXPERIMENTAL PROGRAM

Variables examined

The key variables in a fundamental study of fiber screening can be grouped into four categories:

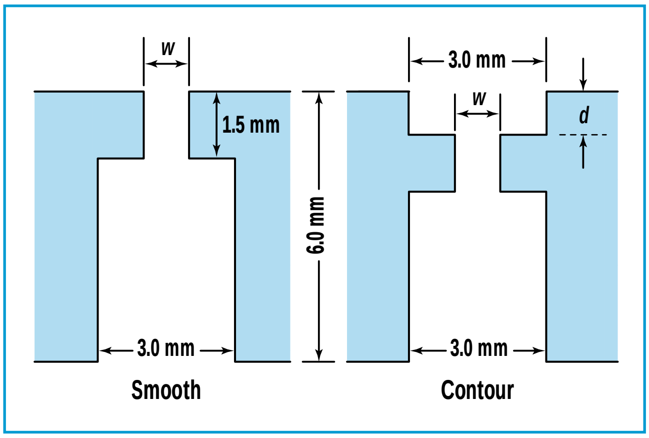
1. Fiber: length, diameter, stiffness
2. Aperture: size, shape, spacing
3. Flow: upstream velocity, aperture velocity, upstream turbulence
4. Suspension: consistency (concentration)

Figure 2 illustrates a few of these key variables: the slot width, w; fiber length, l; upstream velocity, V_U; and the slot velocity, V_S.

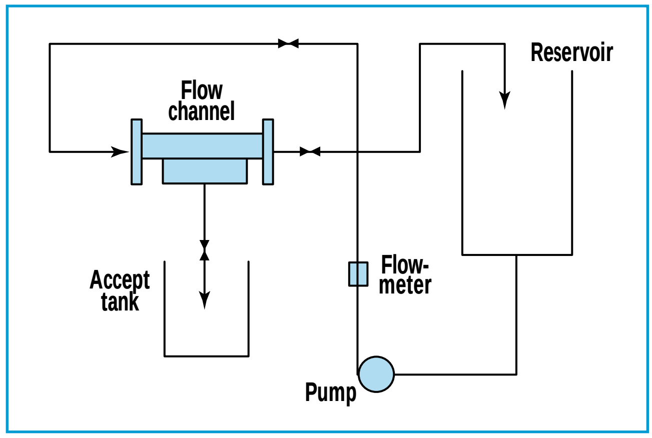
Eleven fiber furnishes were used in this study, and their properties are summarized in **Table I**. The kraft and CTMP (chemithermomechanical pulp) fibers were commercial pulp fibers. The synthetic fibers were included to provide particles with well defined, constant properties. To expedite analysis, a single fiber length was typically used in individual tests. However, fibers of different lengths were sometimes blended together so that the effect of fiber length could be assessed in a single test.

Three slot widths were examined in these tests: 0.25, 0.5, and 1.0 mm, with most of the tests being conducted with the 0.5 mm slot. These widths embrace the range of slots widths historically used in industry, although there has been a recent trend to slots as small as 0.15 mm. What has made small slots practical has been the development of screen contours, which are depressions on the feed side of the screen plate. Smooth (i.e., noncontoured) slots were used for the majority of these tests, but two contour slots were also tested. Details of the smooth and contour slot geometries are shown in **Fig. 3**. Various contour designs are found in industry, and a simple rectangular shape was used in this study. The two designs used in this study both had 3-mm-wide contours, but had different contour depths. The "shallow-contoured" slot had a 0.5-mm contour depth, d, while the "deep-contoured" slot had d equal to 1.2 mm.

Upstream velocity could be varied over a range of zero to 12 m/s. Most tests were conducted at 6.5 m/s, which has been estimated to be a typical velocity in a common pulp screen *(7)*. Slot velocity could be var-



3. Dimensions of smooth and contour slots



4. Schematic of the flow loop with single-slot channel

ied over a range of zero to 9 m/s and was used as the principal experimental variable. Typical slot velocities are in the range of 2–4 m/s. A fixed level of upstream turbulence was used throughout the experiments, as discussed later.

Fiber–fiber interaction in the suspensions was minimized by the use of a low concentration in the feed flow, generally in the range of 10^4 fibers per liter. This gave a crowding factor, N, less than 1.0, where crowding factor is defined as the number of fibers in a spherical volume with a diameter equal to the fiber length *(9)*. A value of $N < 1$ signifies that fibers are in a regime of only occasional contact.

Experimental apparatus and procedure

Tests were carried out with a recirculating flow loop that included a flow channel with a single slot perpendicular to the flow. A schematic of the flow loop is shown in **Fig. 4**. It has a reservoir that was used for preparing the pulp suspension and as a supply tank for the pump. To ensure full water absorption, fibers were stored in water in the reservoir for at least 24 h before a test. This also allowed the suspension to reach the ambient temperature of 18–20°C.

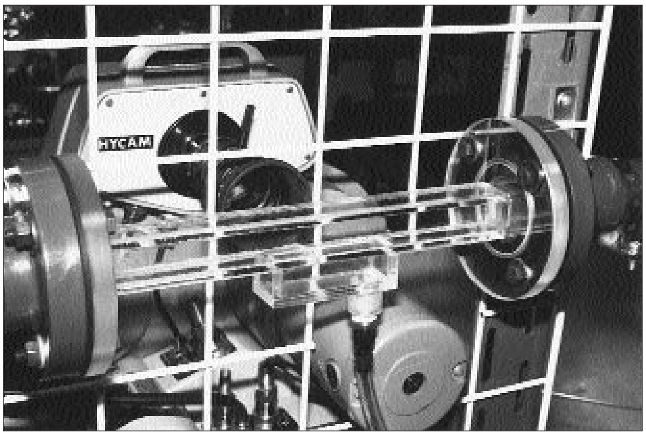
A centrifugal pump drove the flow through the loop, which consisted of a flow channel and a series of 38-mm-diam. pipe sections. Between the pump and channel, a flow-control valve and magnetic flow meter were used to regulate the feed flow. Downstream of the channel, the flow passed through a control valve and returned to the reservoir. The flow that passed through the channel slot passed to the accept tank via the accept line and flow control valve. The accept line was made of flexible tubing that could be squeezed to backflush the slot before the start of a test to purge air from the channel's accept chamber, or to clear the slot of fiber accumulations.

Fiber type	Length,[a] mm	Diameter, mm	Stiffness, 10^{-12} N·m²
Nylon	3.1	0.230	2.9×10^5
15 denier	1.0	0.043 [b]	350
15 denier	1.5	0.043 [b]	350
15 denier	3.1	0.043 [b]	350
Rayon			
4.5 denier	1.0	0.012 [b]	0.5
4.5 denier	1.2	0.020 [b]	4
Kraft pulp			
Whole pulp	0.5–5.0	0.030	4 [e]
Fractionated pulp [c]			
P10/R14	3.3	0.030 [d]	4 [e]
P14/R28	2.6	0.030 [d]	4 [e]
R12	3.2	0.030 [d]	4 [e]
CTMP	0.5–3.0	0.030	100

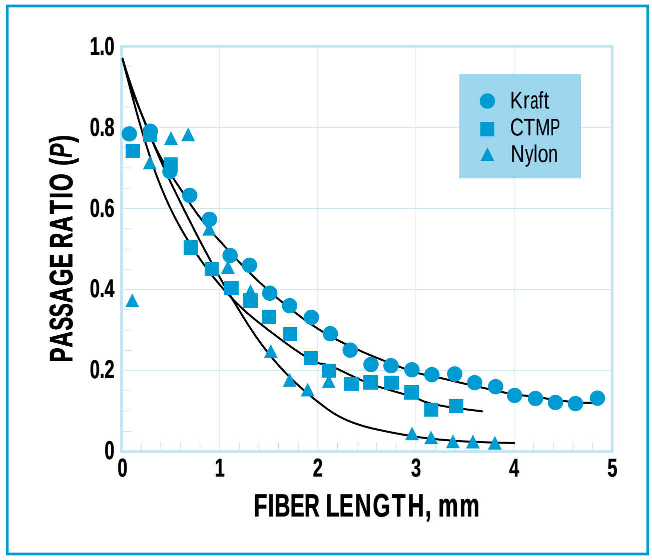
[a] Fiber length measured with a Kajaani FS-100 fiber-length analyzer
[b] Calculated from fiber denier and density
[c] Fiber fractions obtained by passage through (P) and retention on (R) screens of various mesh in a Bauer–McNett fiber-length classifier
[d] Average fiber width of 0.035 mm
[e] Average value for softwoods

I. Fiber properties

The flow channel consists of two chambers, as seen in **Fig. 5**. The feed chamber of the channel is 350-mm long and 20-mm square in cross-section, with both dimensions based on geometric features of an industrial screen. The length is approximately the distance between the turbulence/pulse generating elements of a screen rotor, while the channel height corresponds to the distance between the screen plate and rotor surface. The Reynolds number in the test section (based on an equivalent channel diameter) is approximately 1.3×10^5. The level of turbulence at the slot is estimated from a similar flow in a pipe where turbulence intensity—at a location 10 diameters downstream of an abrupt contraction—was approximately 0.09 at the center and 0.30 near the wall *(10)*. Slots were located in the bottom wall of the flow channel. The flow through the screen slot passed into an accept chamber that was 19-mm square in cross-section. The shape



5. Plexiglas flow channel



6. Effect of fiber length on passage ratio for a range of fiber types ($V_s \approx 2$ m/s , $V_u \approx 6.5$ m/s, w = 0.5 mm)

and size of the slot was a key experimental variable. For a slot velocity of 4 m/s and a characteristic slot width of 0.5 mm, the Reynolds number for the flow through the slot was 2×10^3.

The steps followed to measure passage ratios were:

1. Set up the system with the desired operating conditions.
2. Sample the upstream and accept flows.
3. Measure the fiber concentration in each sample.
4. Determine *P* by taking the ratio of these concentrations (Eq. 3).

To accomplish the first step, the desired fiber type and slot coupon were installed in the system. The upstream velocity was determined by dividing the total upstream flow (measured using the magnetic flow meter) by the cross-sectional area of the feed chamber. The flow was adjusted to reach the target value. Likewise, the slot velocity was determined by dividing the total accept flow (measured by timing the discharge of the accept line into a calibrated container) by the minimum cross-sectional area through the slot.

To sample the upstream flow, the return flow to the reservoir was momentarily diverted to a sampling container (with the accept flow stopped). Sampling the accept flow was accomplished by discharging the accept flow directly into a container, as shown in Fig. 4. Each of these samples was then subsampled for analysis. The concentration of fibers was measured using either a Kajaani FS-100 fiber length analyzer or by draining a carefully measured volume of the suspension on a filter paper and manually counting the fibers.

To complement the measurements of passage ratio, some photographs were taken of fibers that were immobilized or "trapped" on the downstream edge of the slot. The intent was to use these images to get some insight into the mechanisms that control fiber passage. Previous work *(4)* had recognized fiber trapping as an intermediate step in fiber passage. Photographs of fibers at the aperture entry were obtained using a 35-mm camera with back illumination from four 300-W quartz bulbs shining through a light diffuser.

RESULTS AND DISCUSSION

Fiber variables

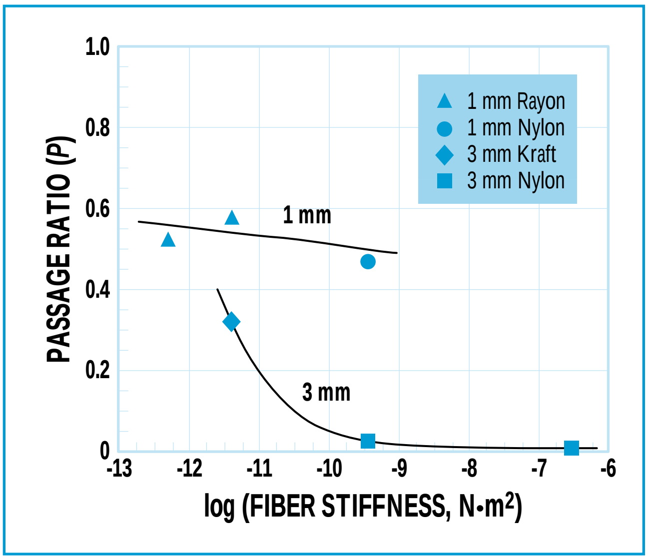
Fiber length was found to have a strong influence on passage ratio for a wide range of fiber types, as shown in **Fig. 6**. When fiber length is close to zero, *P* approaches 1.0. This is reasonable, since infinitesimally small fibers would be expected to follow the flows that divide at the slot. As fiber length, *l*, increases to several times the slot width, *w*, passage ratio decreases, which is consistent with the "wall effect" and "turning effect" mechanisms mentioned previously. More specifically, Fig. 6 shows that *P* has decreased to a value less than 0.3 when $l > 3$ mm (i.e., $l/w > 6$), even for the flexible kraft fibers.

The influence of fiber flexibility is seen in Fig. 6 to be secondary to the influence of length. Still, for fibers of significant length (i.e., $l/w > 2$), the more flexible fibers (such as the kraft fibers) exhibited higher passage ratios. This is reasonable, since saturated fibers have nearly the same density as water, and an infinitely flexible fiber in steady flow could follow the curved streamlines that turn and pass through the slot. For short fibers, the influence of flexibility was not significant because *P* approached 1.0 even for stiff fibers. These effects are shown explicitly in **Fig. 7**.

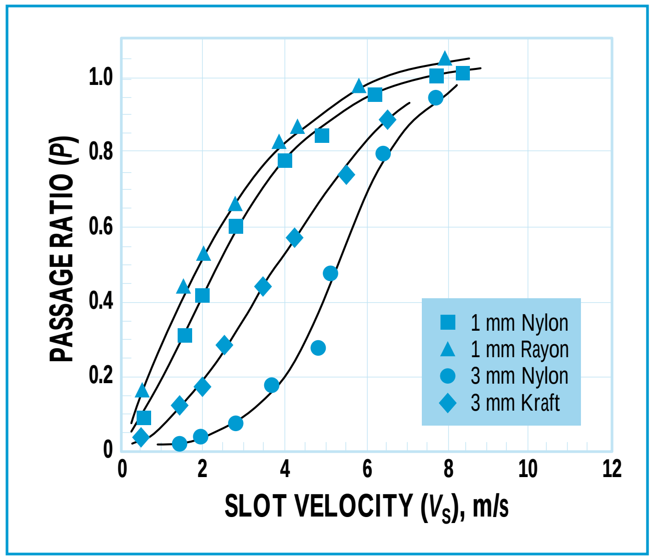
Flow variables

Slot velocity, V_s, also has an important effect on *P*, as shown in **Fig. 8**. Increasing V_s increases *P*. This was noted previously for industrial screens, and indeed there is good agreement between the industrial data for pulp shown in Fig. 1 and the data for short fibers in Fig. 8.

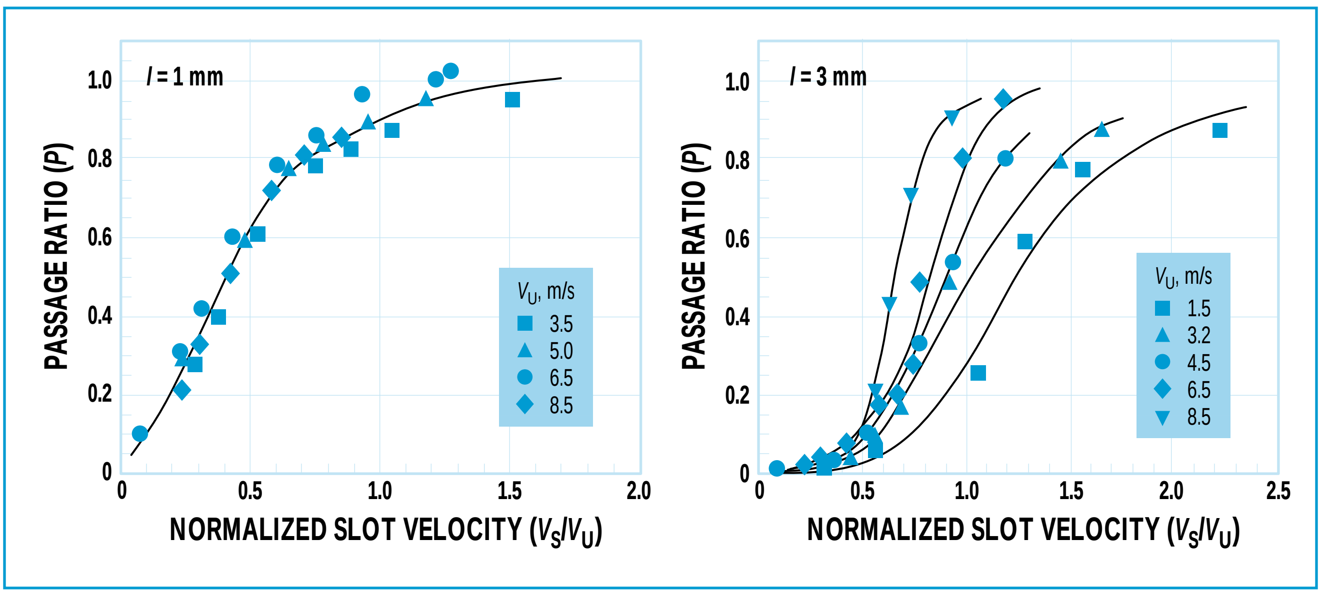
However Fig. 8 also shows that the nature of the increase between *P*



7. Effect of fiber stiffness on passage ratio for a range of fiber types ($V_s \approx 2$ m/s, $V_U \approx 6.5$ m/s, w = 0.5 mm)



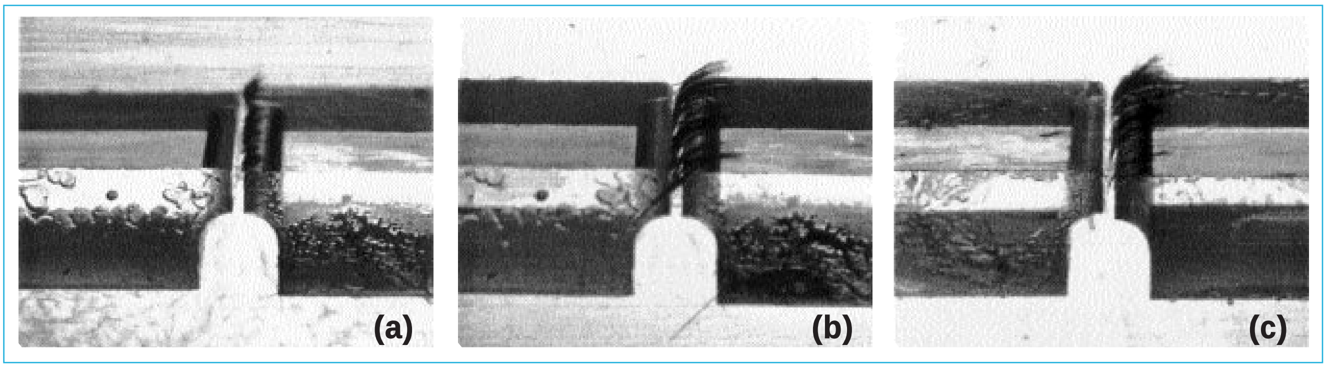
8. Effect of slot velocity on passage ratio for a range of fiber types ($V_U \approx 6.5$ m/s, w = 0.5 mm)



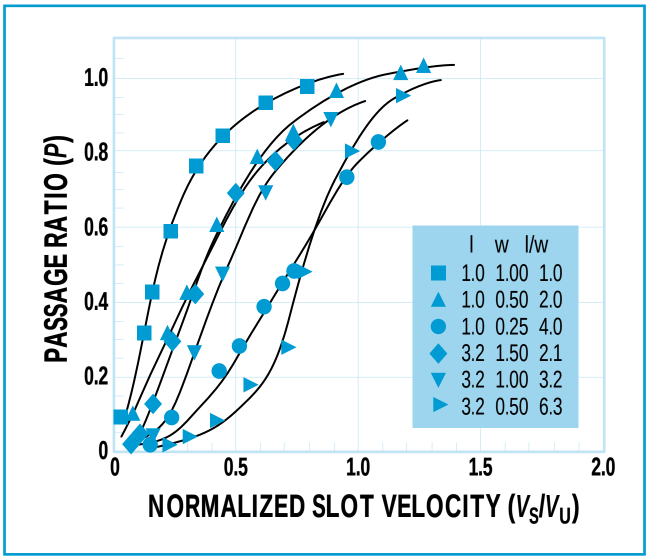
9. Effect of normalized slot velocity on passage ratio for 1-mm fibers (left) and 3-mm fibers (right) (nylon fibers, w = 0.5 mm)

and V_S differs for fibers of differing length and stiffness. For short fibers, P increases rapidly with V_S up to a value of about 4 m/s, then P asymptotically approaches a value of 1.0 with further increases in V_S. This concave-downward form of the P–V_S curve will be called a "C" curve here. It is seen to apply for short fibers regardless of their stiffness. A different, more complex form of curve is found for long, stiff fibers. As shown in Fig. 8, the value of P initially increases slowly and remains close to zero even for appreciable V_S. There is then a transition point where P increases sharply over a narrow range of V_S. This is followed by an inflection point, a decrease in the slope of the curve, and P approaches 1.0 asymptotically at large V_S. This form of curve will be termed an "S" curve.

The other main flow variable is the upstream velocity, V_U, which is closely related to the rotor tip speed in industrial screens. Higher values of V_U cause a reduction in P. It is useful to examine P as a function of the ratio of V_S/V_U, which will be termed the "normalized slot velocity." This ratio determines the thickness of the layer of fluid that turns into the slot (the "wall effect") but not necessarily the magnitude of the hydrodynamic drag forces through and past the slot (the "turning effect"). **Figure 9** shows the effect of V_S/V_U on P for 1-mm- and 3-mm-long fibers.



11. Photographs of nylon fibers trapped on the downstream edge of a slot for different fiber lengths and velocity ratios. (a): 1-mm fibers, V_s/V_U = 0.4; (b): 3-mm fibers, V_s/V_U = 0.4;(c): 3-mm fibers, V_s/V_U = 0.8 ($V_U \approx$ 6.5 m/s, w = 0.5 mm)



10. Effect of fiber length and slot width on the **P–V**$_s$ *curve (nylon fibers,* $V_U \approx$ *6.5 m/s)*

Slot variables

Slot width is perhaps the most important design variable in pulp screening. Wider slots naturally increase the value of *P*. But **Fig. 10** shows that slot width also has an important influence on the transition from C-type behavior to S-type behavior, which is shown here for various ratios of fiber length to slot width (*l*/*w*).

The transition is seen to occur at $l/w \approx 2$, with C-type behavior below this value and S-type behavior above it. A physical explanation for this transition is suggested in the photographs of **Fig. 11**. The long and short fibers shown here both entered the slot and became "trapped" on the downstream edge of the slot, pivoting about the edge. The short fibers are held in place by a hydrodynamic moment balance caused by fluid forces only (Fig. 11, left). In contrast, for the long fibers, the end inside the slot comes into contact with the upstream wall of the slot during trapping (Fig. 11, middle). This wall contact provides an additional force in the moment balance holding the fiber in place. When V_S is increased (Fig. 11, right), the increased hydrodynamic drag on the fiber first diminishes the wall force to zero, and only then becomes an additional force causing the fiber to tip into the slot and pass through. This threshold value would determine the transition point in the P–V_S curve. In contrast, for short fibers, increases in V_S continuously increase the hydrodynamic force that tips the fiber into the slot.

Not all fibers trap before passage. The upstream "wall effect" may also include a threshold mechanism, but the trapping mechanism described here may well be the principal factor accounting for the S and C shapes of the P–V_S curves.

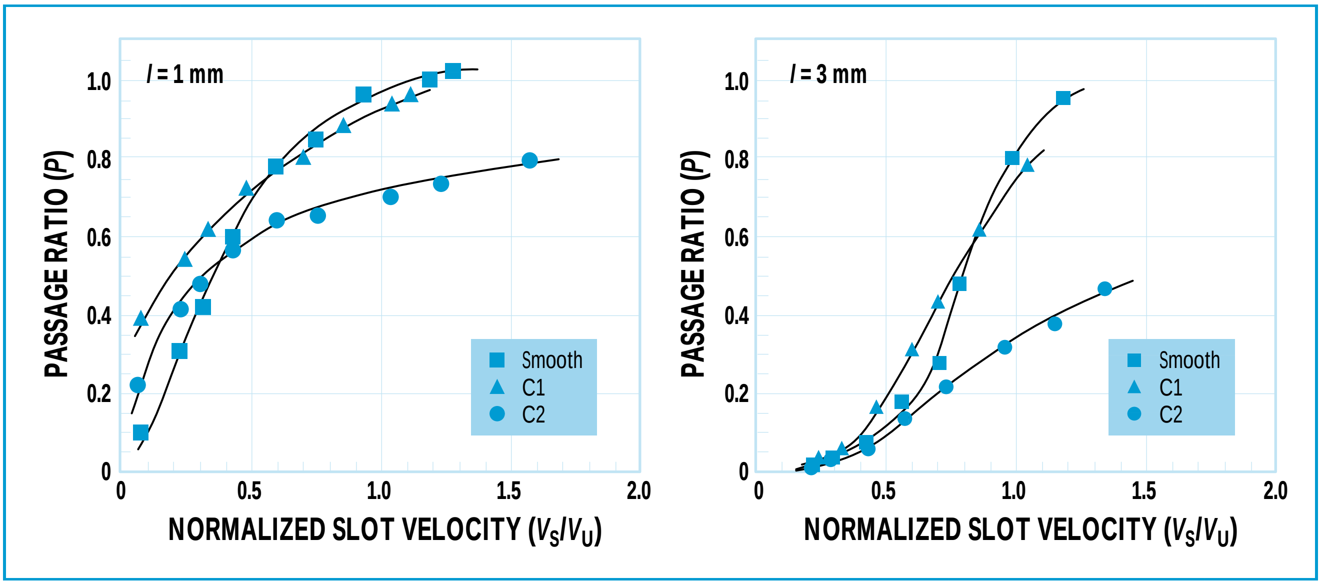
The previous observations are for stiff fibers. In the case of flexible fibers, short flexible fibers behaved like short stiff fibers, but long flexible fibers showed behavior somewhere between short and long stiff fibers (S and C behavior). This likely occurs because increasing slot velocity induces substantial bending on the downstream edge rather than simply reducing contact with the upstream wall.

Tests with contour screen slots (shown in Fig. 3) provided results that were similar to those with the smooth slot. In particular, the shallow-contoured slot (C1) gave a C-type behavior for short, stiff fibers, but with a higher value of *P* at low normalized slot velocities, as shown in **Fig. 12** (left). For the long, stiff fibers (Fig.12, right) this contour provided an S-type curve with slightly higher values of *P* at low V_S/V_U.

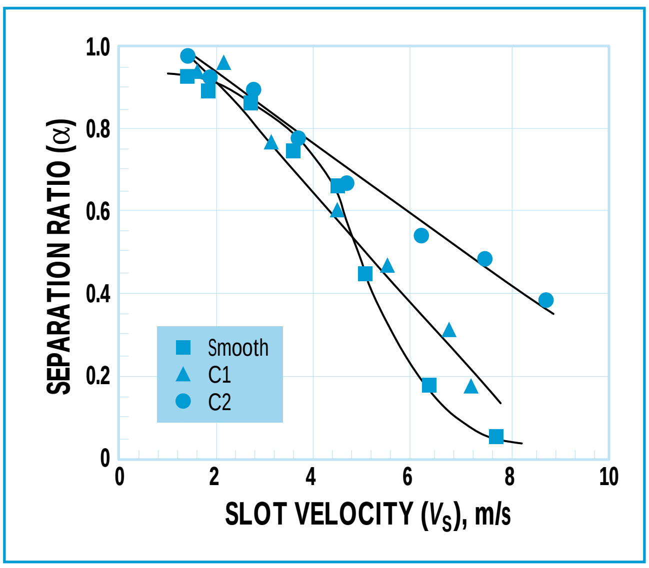
The deep-contoured slot (C2) also yielded a C-type curve for short, stiff fibers with lower values of *P* than the shallow-contoured slot. Its values of *P* are higher than those for the smooth slot at low V_S/V_U, but substantially lower at high V_S/V_U. For the long, stiff

KEYWORDS

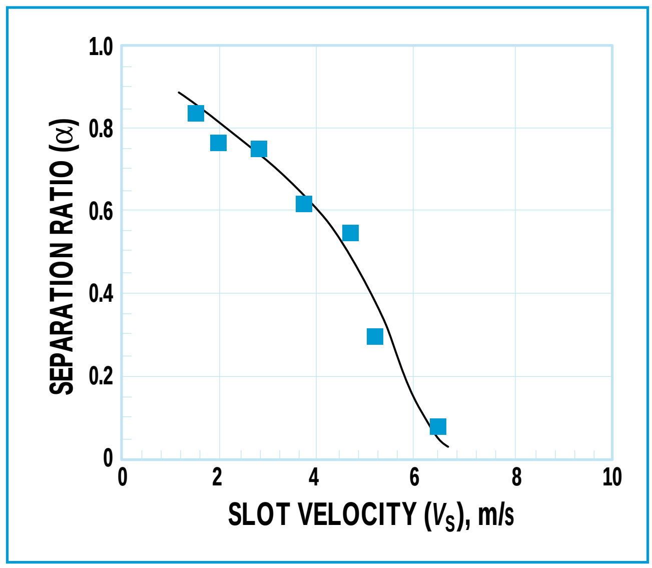
Fibers, slits, screening, screens, properties, velocity, flow, equations, variables, test methods, fiber length, consistency.



12. Effect of slot velocity on passage ratio for smooth and contour slots for 1-mm fibers (left) and 3-mm fibers (right) (nylon fibers, w *= 0.5 mm)*



*13. Separation ratio vs. slot velocity for long/stiff vs. short/stiff fibers for smooth and contour slots (*w *= 0.5 mm)*



*14. Separation ratio vs. slot velocity for long/stiff vs. long/flexible fibers for smooth slot (*w *= 0.5 mm)*

fibers, the values of *P* are lower with the deep-contoured slot than either the shallow-contour or smooth slot. Moreover, not only is *P* low, but the rate of increase of *P* is lower. The complex response of *P* to the presence of a contour discourages any simplistic model of passage ratio.

Separation ratio

As noted previously, screen efficiency depends on the separation ratio, α. One can estimate α from the measured values of *P* (Eq. 5). Such estimates are shown for the separation of long/stiff and short/stiff fibers in **Fig. 13** and for long/stiff and long/flexible fibers in **Fig. 14**. In all cases, α decreases with increasing V_S. The curve for the smooth slot has a somewhat complex shape, with the rate of decrease changing for different ranges of V_S (Fig. 13). The curve for the contoured slots, however, showed a nearly linear decrease. Thus, while the three slot geometries had comparable values of α at very low V_S, the C2 contour came to have distinctly superior α at high V_S.

The values of α for the separation of long/stiff fibers from long/flexible fibers for a smooth slot are shown in Fig. 14. (Contoured slots were not tested.) Here α shows a somewhat similar form to that in Fig. 13, but the levels of α at low V_S were not as great as those in Fig. 13.

CONCLUSIONS

The findings of this study suggest that a fiber length/slot width (l/w) ratio of approximately 2 is a critical value in pulp screening. Below this level ($l/w < 2$), the passage ratio of stiff and flexible fibers shows a similar and somewhat simple dependence on slot velocity and upstream velocity, as defined by the C-type curve. Above this value, fibers may exhibit the more complex dependence on slot velocity defined by the S-type curve. Fiber flexibility becomes important in determining whether a C-curve or S-curve form applies when $l/w > 2$.

These findings have implications for shive screening and the fractionation of long, coarse fibers from pulp. They suggest that optimal levels of separation occur at very low slot velocities where the passage ratio of long fibers remains low, but that of the short fibers is significant.

The findings of this study also suggest that both the slot velocity and its ratio to the upstream velocity are important in screen operation, through passage ratio, P, and separation ratio, α. In the derivation of the performance equations (Eqs. 1 and 2), it was assumed that α was independent of slot velocity *(1)*. This is clearly not the case. The variability of α means that Eqs. 1 and 2 are only valid in cases where V_S and V_U (slot velocity and upstream velocity, respectively) are maintained constant. In an industrial application, this would imply that the performance equations should only be applied when the rotor speed is maintained constant (i.e., constant V_U) and the slot velocity is constant (i.e., a constant accept flow). This is not unduly restrictive. Thus it appears possible to estimate screen performance from measurements of P and α at individual apertures, as described in this study.

It should be noted that these experiments were carried out under idealized conditions with extremely low fiber concentrations and in the absence of the rotor induced pulses found in industrial screens. These factors have an effect on fiber passage and should be the subject of future study. TJ

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