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Continuous Separation of Fines from Fibers in a Wedge-Shaped Vessel

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ABSTRACT

The continuous removal of fines from a pulp suspension can be achieved by a particle elutriation process using, for example, a wedge-shaped vessel with an inclined tube at one vertical end wall that serves as an inlet for the suspension. Near the other vertical end, the suspension flow is split into a bottom stream containing the recovered pulp and a top stream containing the separated fines. The effect of operating conditions on both the hydrodynamic behavior and the separation efficiency was investigated. There are two critical limits for the operating flow rates of the feed suspension: below a minimum flow rate, fibers settle near

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the bottom exit and above a maximum flow rate, fibers escape in the top stream. These limiting flow rates do not show a strong dependence on operating conditions, except for a maximum inlet consistency above which the pulp bed expands into the outlet section, thus preventing fractionation. The particle concentration in the top stream was measured with a spectrophotometer, from which the separation efficiency was determined as a function of the inlet and outlet flow rates and the inlet consistency. The separation efficiency increases with increasing split ratio (i.e., the ratio of top to bottom streams) and with decreasing consistency of the feed suspension. Fiber loss in the top stream is about 1% of the fibers entering the vessel.

Key Words: Elutriation; Spouting; Fines separation; Separation efficiency; Separation Mechanisms.

INTRODUCTION

Efficient separation of fines from the long fiber fraction of fibers in a pulp suspension would allow the separate treatment of fines and fibers in bleaching and wet-end papermaking operations. This might provide advantages over treating the whole suspension. For instance, hard to bleach fines could be bleached differently than the whole fraction; whereas treating fines and fibers separately in the wet-end could lead to a more effective use of papermaking additives or to a better control of fines flocculation and deposition of fines on fibers.

Small particles, other than fines, often need separation from fibers, such as ink particles and stickies, in the paper recycling process. Presently, these particles are dislodged from the fibers during repulping and removed from the fiber suspension by washing and flotation.[1–4]

A new ink removal technique based on hydrodynamic principles was developed by the authors.[5–7] This new separation technique is based on spouting pulp fibers by an upward liquid flow,[5] which upon rising through the vessel, elutriates the ink particles out of the vessel.[6] The process was developed for a semibatch operation mode. The spouting characteristics of pulp fibers, as well as the theory underlying particle elutriation using a conical vessel in semibatch mode, were reported earlier.[5–7] In this article, a continuous elutriation-spouting process in a wedge-like vessel is demonstrated at the laboratory scale. This geometry was chosen because the flow in the vessel has a strong, upward component, thus mimicking some of the flow conditions in the conical vessel studied previously.

EXPERIMENTAL APPARATUS AND PROCEDURE

The wedge-like vessel used in this study is shown in Fig. 1. It consists of a lower diverging channel of 30-degree angle connected to an upper converging channel of a 60-degree angle. The total height of the vessel is 36.6 cm and the length is 25.4 cm. The vessel is closed at the bottom and the top by flat strips with widths of 12 and 10 mm, respectively. Five identical tubes of 3-mm ID spaced 5 cm apart were connected to the top strips as an outlet for the stream containing the elutriated particles. The outermost tubes are 2.7 cm from the vertical side walls. The suspension inlet is a tube of 1-cm ID inclined at an angle of 31degrees between its axis and the vertical vessel wall. It is placed at a height of 11.5 cm from the bottom of the vessel and centered at that height. The bottom outlet is a vertical tube of 1-cm ID placed adjacent to the vertical wall at the opposite end from the inlet. The vessel and the tubes are made from Plexiglas.

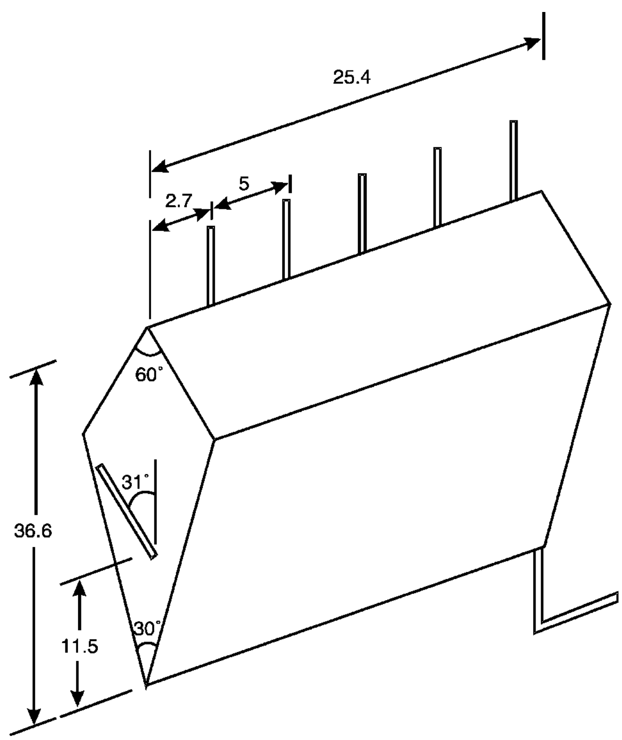

Figure 1. Wedge-like vessel used in continuous fines separation process. Dimensions in cm.

The system flowsheet is shown in Fig. 2. A continuously mixed vessel of about 37-L volume is the main reservoir for the pulp suspension. A pulp suspension was prepared using the thermomechanical treatment method,[6] and was transported by a centrifugal pump to a tank designed with an overflow to provide a constant head feed for the process vessel. The overflow was circulated back to the pulp reservoir. The circulation rate was high enough to keep the solids suspended in the constant head vessel. The suspension feed (S) flowed by gravity to the wedge-like process vessel. The flow rates were

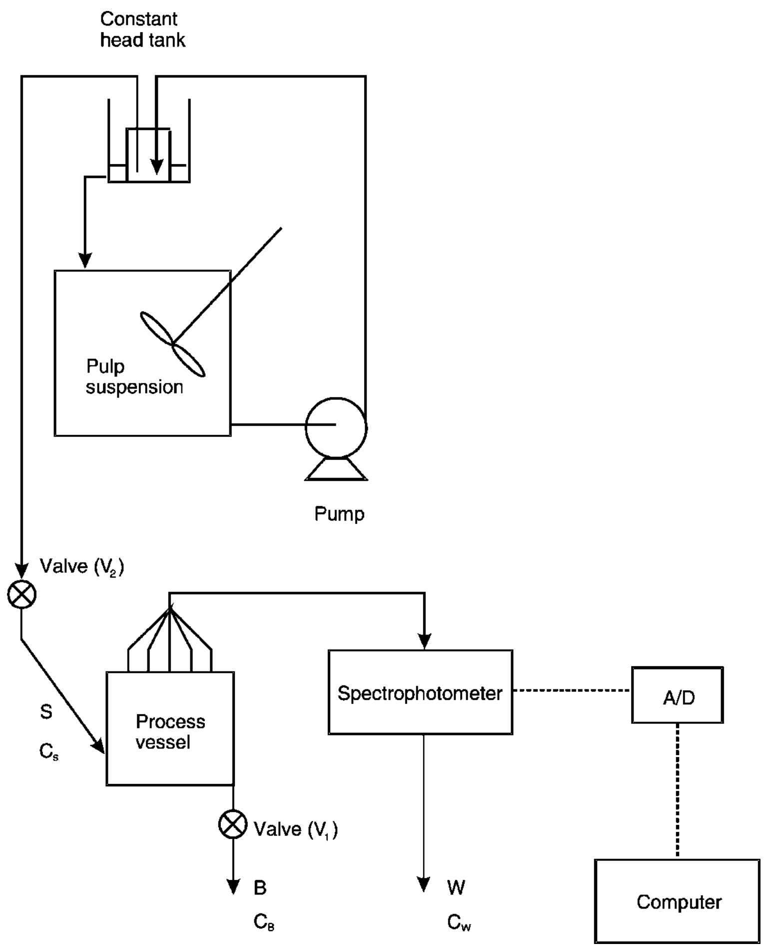

Figure 2. Experimental set-up.

controlled manually by valves (V_1 and V_2). Within the process vessel, the suspension was split into a bottom stream (B) containing the recovered pulp and a top stream (W) containing the elutriated particles. The top stream passed though a spectrophotometer to measure the transmittance.[6] The measured transmittance was shown on the computer screen in real time. The concentration of fines was determined by the Beer–Lambert law.

To investigate the mechanism of particle separation, experiments were performed with suspensions of small particles (Avicel particles of 20 μm size, cf [6]) and fines-free suspensions (kraft hardwood). Both suspensions were prepared as described in reference 6. In these cases, the bottom stream flowed through a second spectrophotometer, which was also connected to the computer. For experiments with fines-free fiber suspensions, the percentage fiber loss from the feed in the top stream was determined by filtrating a known volume of the top stream over a 150-mesh screen.

The suspension feed rate was determined from the overall mass balance. Since the flow rates were adjusted manually, it was difficult to set them to the required values. The accumulation of fibers within the vessel during the time required to reach steady state caused a deviation in the flow rates from the preset values. As a result, there is an error of a few percent in the flow rates.

In addition to the determination of particle concentration in the top stream, small samples of the suspensions from both the feed and the bottom streams were taken and subsequently dried to determine the solid content.

DATA AND ANALYSIS

A typical experiment required about 30 minutes to reach steady-state operation since the volume of the process vessel is large (about 7.5 L). A typical example of a start-up transient is shown in Fig. 3 for the case of an inlet consistency (X_s) of 0.5 g/L, a feed flow rate of 740 mL/min, and a split ratio (W/B) of 1.4. The figure shows the measured transmittance of the top stream as a function of time for an experiment with a recycled pulp suspension fed into a liquid-filled, solid-free vessel. The transmittance decreased with time to a constant value of T_{ws} at steady state.

The separation efficiency η is defined as the fractional removal of small particles from the feed suspension at steady state, i.e.,

$$\eta = \frac{C_w W}{C_s S} \tag{1}$$

where W and S are the flow rates of the top stream and the feed suspension and C_w and C_s are the particle concentrations in W and S, respectively. Since all

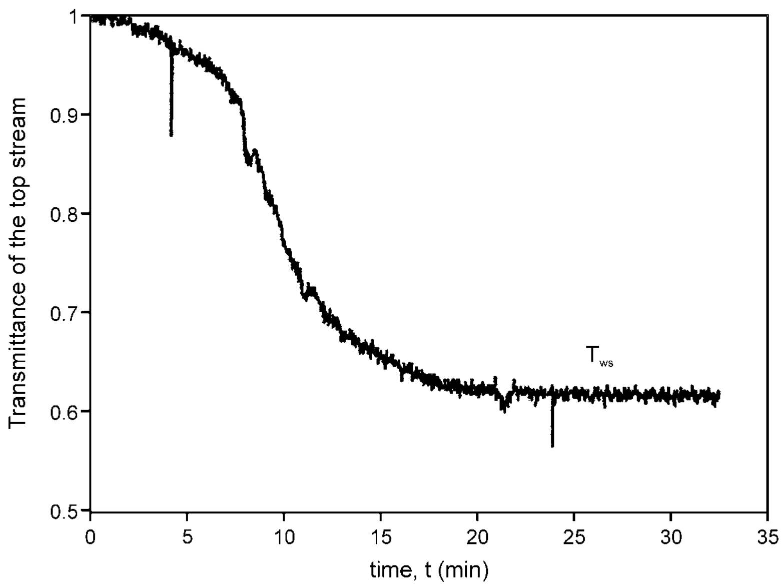

Figure 3. A typical example of the measured transmittance of the top stream as a function of time for an experiment with a recycled pulp suspension fed into a liquid-filled, solid-free process vessel. $X_s = 0.5\,g/L$; $S = 740\,mL/min$; and $W/B = 1.4$. The steady state transmittance is T_{ws}.

streams have densities close to 1 kg/L, the overall mass balance may be written as

$$S = W + B \tag{2}$$

where B is the flow rate of the bottom stream. Combining eqs. 1 and 2:

$$\eta = \frac{C_w}{C_S}\frac{W/B}{1 + W/B} \tag{3}$$

The experimental separation efficiency was calculated from eq. (3) using C_w determined from the measured steady state transmittance (T_{ws}) through the Beer–Lambert law:

$$Cw = \frac{1}{Ab}\ln\left(\frac{1}{T_{ws}}\right) \tag{4}$$

where A and b are the absorptivity and the path length, respectively. An approximate value of the product Ab for fines from a recycled pulp suspension was determined from experiments with the conical vessel.[6] In the semibatch process, the initial transmittance of the exit suspension corresponded to the initial concentration of fines. Measuring the initial transmittance with different initial solids hold-ups, and knowing that the initial fraction of small particles (ink and pulp fines) was about 0.35, gave the transmittance-concentration calibration. The curve is shown in Fig. 4. Using eq. (4), it follows from the slope of Fig. 4 that $Ab \simeq 3.0\,L/g$.

The concentration of particles in the feed, C_s, may be expressed as a fraction of the inlet consistency:

$$C_s = yX_s \tag{5}$$

where y is the fraction of fines in the total suspended solids (g fines/g total pulp) and X_s is the feed consistency (g pulp/L suspension). Typical values of y are in the range of 0.3 to 0.4. Combining eqs. (3 through 6) yields the following equation, which was used to calculate the separation efficiency from experimental values of the feed consistency, the split ratio, and the steady-state transmittance of the top stream:

$$\eta = F\frac{W/B}{1 + W/B}\frac{1}{X_s}\ln\left(\frac{1}{T_{ws}}\right) \tag{6}$$

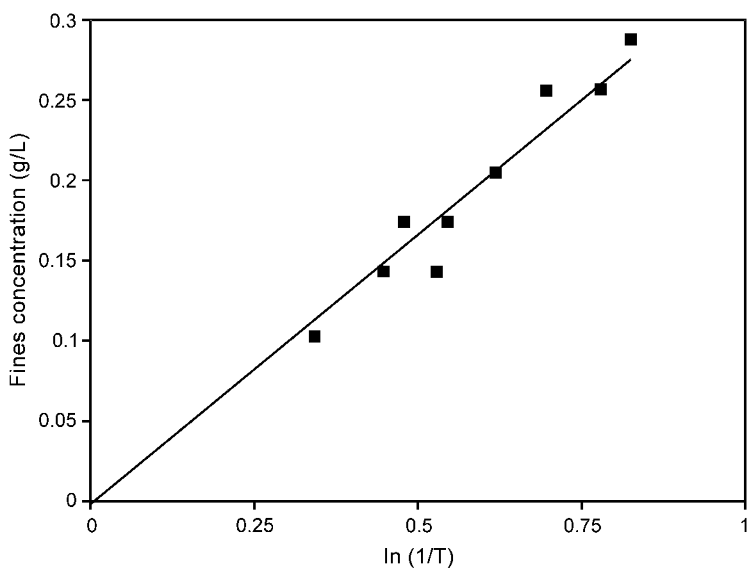

Figure 4. Calibration curve of the spectrophotometer for suspensions of fines from a recycled pulp suspension.

where

$$F = \frac{1}{yAb} \tag{7}$$

For a given feed suspension, A is constant. For the recycled pulp used here, $y \approx 0.35$ and $F = 1.02 \pm 0.03\,g/L$.

RESULTS AND DISCUSSION

Spouting Mechanism

Fines can be separated from fibers if at some height in the process vessel the liquid velocity is higher than the terminal settling velocity of the fines and less than that of the fibers (which are mainly in the form of flocs).[6,7] This requirement is achieved when the suspension is fed between certain limiting flow rates. The flow pattern for successful operation is shown schematically in Fig. 5A. The increase in the cross-sectional area of the vessel in the vertical direction satisfies the required conditions for the settling of fiber flocs after they rise to a certain height within the vessel. The horizontal flow near the bottom of the vessel is strong enough to prevent the permanent accumulation of fiber mass. This horizontal flow is split into an upward flow and a downward bottom stream. The resulting bed consists of a continuous phase of a fiber floc suspension filling the lower part of the vessel. The ratio of upward to horizontal flow increases with the split ratio W/B.

At low feed rates, fibers tend to settle near the bottom exit where the horizontal flow splits (see Fig. 5B). For a fixed ration of W/B, when the feed flow rate is decreased below S_{min}, a mass of fibers accumulates near the bottom outlet and grows with time as more fibers settle. As the fiber mass grows, the flow rate of the bottom stream decreases until the process terminates.

In addition to the lower limit on the feed flow rate (S_{min}), there is an upper limit at which flocs of fibers escape in the top stream. The height of the pulp suspension phase within the vessel is a function of the inlet flow rate. At moderate flow rates, the surface of the pulp bed is nearly flat (see Fig. 5B). At higher flow rates, the suspension surface rises near the opposite wall of the vessel (see Fig. 5B). This height increases with increasing inlet feed flow rate up to a flow rate (S_{max}) where the pulp suspension reaches the first tube exit and fiber flocs are carried out of the vessel, resulting in considerable fiber loss.

The lower (S_{min}) and the upper (S_{max}) operating feed rates were determined experimentally as function of the flow split ratio (W/B) and the inlet consistency (X_s). Results are shown in Fig. 6. The inlet consistency did

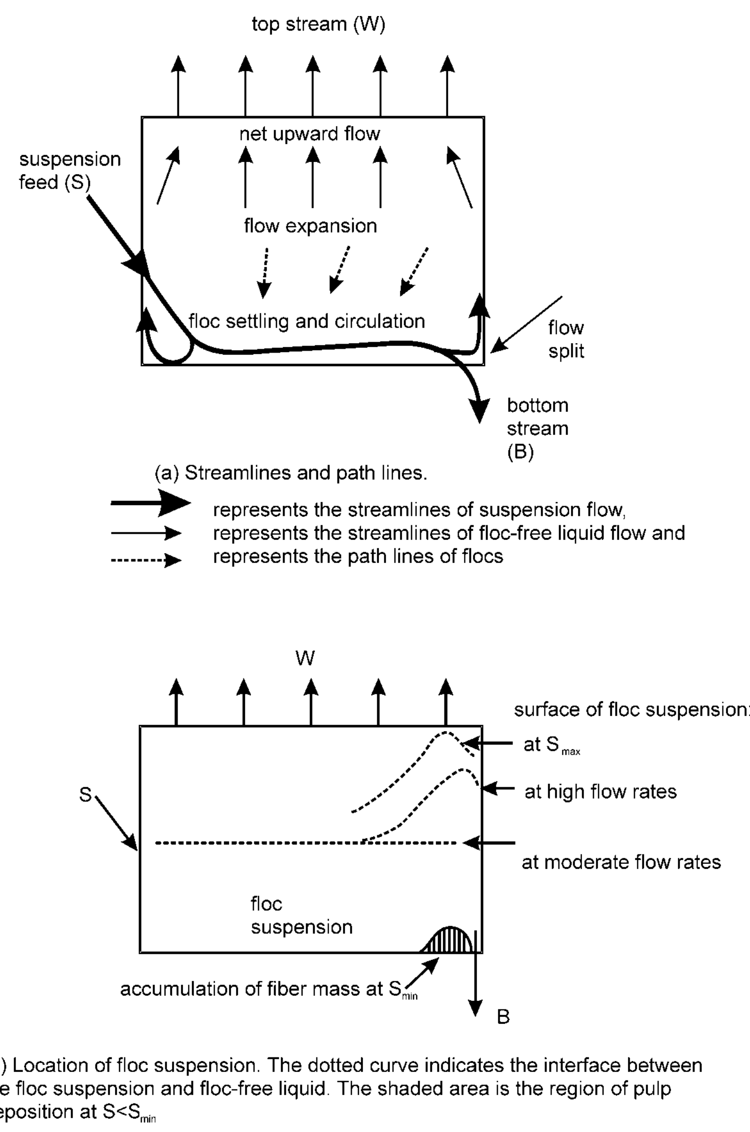

Figure 5. Schematic representation of flow in process vessel.

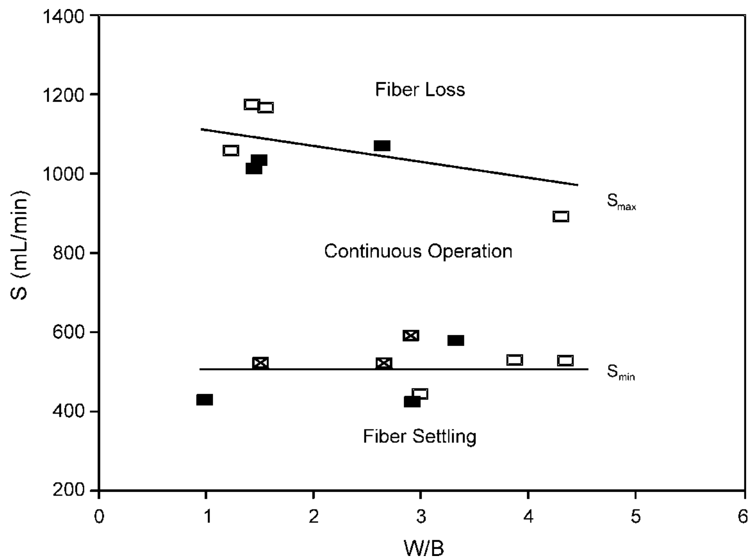

Figure 6. Regimes of operation. The symbols refer to different inlet consistencies: empty square for 0.5 g/L; square with cross for 0.8 g/L; and filled square for 1.0 g/L.

not cause a measurable change in S_{min} and S_{max} for values between 0.5 to 1.0 g/L. When X_s was increased to about 2.0 g/L, the pulp suspension filled the whole vessel, resulting in the fiber carryover. A value of $X_s \approx 1.5\,g/L$ represents the maximum inlet consistency for this geometry. The split ratio has little effect on S_{min}, but for S_{max} there is a tendency to decrease with W/B. This can be explained by a larger upward flow component at higher values of W/B, which requires a higher value of S_{max} to prevent fiber loss. As an approximation, S_{max} and S_{min} can be considered to be 1 and 0.5 L/min, respectively, for the vessel used in this work. The limiting flow rates should depend on geometric parameters, which were not varied, such as the design of the inlet and outlets, the position and direction of the feed tube, the vessel height, angles, and so forth.

Separation Mechanisms

If the fines are so small that their settling velocity is much less than the liquid velocity, they may be considered as mathematical points in the flow field. If the particles do not interact with the flocs, the particle concentration is the same in all streams ($C_w = C_s$) and from eq. (3), the separation efficiency is determined only by the flow split ratio, i.e.,

$$\eta_s = \frac{W/B}{1 + W/B} \tag{8}$$

and the solids recovery R_s (g recovered solids / g solids in the feed) is given by

$$R_s = 1 - y\eta_s \tag{9}$$

Experiments were performed with pulp-free suspensions of Avicel particles fed into a liquid-filled, solid-free process vessel. The dimensionless exit concentrations of the two outlet streams, C_w/C_s and C_B/C_s, were determined from measured transmittances. Figure 7 shows these concentrations as functions of time for a feed concentration (C_s) of 0.7 g/L, a feed flow rate (S) of 750 mL/min, and a split ratio (W/B) of 1.8. At steady state, the two exit concentrations approached the feed concentration, confirming that for these small particles (~ 20 μm) the separation efficiency is given by eq. (8).

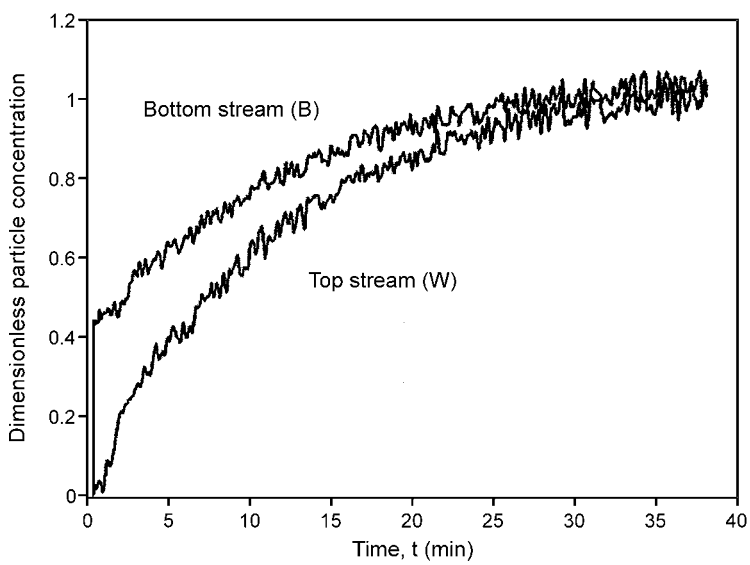

Figure 7. Dimensionless particle concentrations (C_w/C_s and C_B/C_s) as functions of time for a pulp-free Avicel particle suspension. $C_s = 0.7$ g/L; S = 750 mL/min; and W/B = 1.8.

On the other hand, when the settling velocity of the suspended particle is large enough compared to the upward liquid velocity, they can be excluded from the top stream. This is the case of fiber flocs; they are large enough, so they leave in the bottom stream. It could be argued that separation would also occur in a horizontal channel with a well-mixed entrance flow, since fiber sedimentation is larger than fines sedimentation. Splitting the flow by a horizontal plate will result in a top stream depleted of fibers and a bottom stream rich of fibers. The present geometry has the advantage over horizontal flow, in that the upward flow component prevents fiber sedimentation. Figure 8 shows the measured transmittance of the two outlet streams as functions of time for an experiment with a fines-free fiber suspension fed into a liquid-filled, solid-free vessel. The inlet consistency (X_S) was 0.75 g/L, the feed flow rate (S) was 630 mL/min, and the split ratio (W/B) was 2.1. The steady-state value of the transmittance of the top stream is very close to 1.0, which is equivalent to solid-free water, indicating that the fiber concentration in the top stream is small. The fiber loss in the top stream was determined by filtration and drying. The measured percentage fiber loss in the top stream relative to

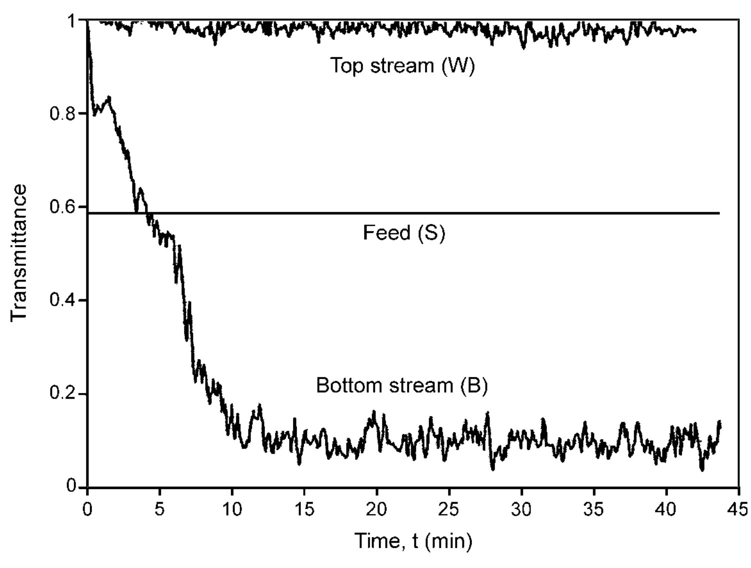

Figure 8. The top and bottom transmittances as a function of time for an experiment with a fines-free fiber suspension fed into a liquid-filled, solid-free process vessel. $X_s = 0.75\,g/L$; $S = 630\,mL/min$; and $(W/B) = 2.1$. The horizontal line is the corresponding transmittance of the feed consistency.

Table 1. Percentage fiber loss in the top stream.

Feed consistency X_s (g/L)	Feed flow rate S (mL/min)	Split ratio (W/B)	Percentage fiber loss
1.1	830	2.9	0.8
1.1	640	1.8	0.2
0.94	690	2.1	1.4
0.94	630	1.4	0.8
0.75	360	2.1	1.8
Average			1.0

fibers in the feed stream is tabulated in Table 1 for different operating conditions. The average fiber loss was about 1%. The fibers were retained in the bottom stream, resulting in an increase in its consistency compared to the feed consistency. Thus, the steady-state transmittance of the bottom stream was much lower than that of the feed.

These results (see Figs. 7 and 8 and Table 1) indicate that the mechanism of the separation in the continuous wedge-like vessel is based on the exclusion of fibers from the top steam and the split of fines into the two streams. The fines split occurs according to the flow split ratio when the fines are very small and fiber flocs do not release short fibers or capture fines. This continuous technique produces a partial separation because fines are retained in the bottom even if no fibers are lost in the top stream. The removal selectivity of small particles can be improved by increasing the split ratio, e.g., for a split ratio of 4 about 80% particle removal can be expected.

For experiments with recycled pulp suspensions, the solid recovery (g in stream B / g in stream S) was measured from the dried samples from the bottom and feed streams. Table 2 shows results at different operating conditions. The last column gives the estimated pulp recovery, i.e., R_s (eq. 9). The experimental results agreed with the estimated values within 10%. This difference is attributed to the errors in determining the solid contents and the flow rates.

Separation Efficiency

The separation efficiency was measured as a function of the split ratio (W/B), the suspension feed flow rate (S), and consistency (X_s). The effect of the split ratio (W/B) on the separation efficiency (η) is shown in Fig. 9 for the case of an inlet pulp consistency of 0.5 g/L and a feed flow rate of 730 mL/min.

Table 2. Percentage solid recovery.

Feed flow rate S (mL/min)	Split ratio W/B	Inlet pulp consistency X_s (g pulp/L)	Pulp recovery (measured) (%)	Pulp recovery (R_s; eq. 9) (%)
670	1.85	0.70	70	77
620	1.73	0.64	73	78
630	1.70	1.50	68	78

The dashed line shows the limiting value, η_s. The experimental results are close to η_s; hence, at low consistency (0.5 g/L) and moderate feed rate, the fines removal is governed by the flow split ratio.

The effect of feed flow rate (S) on the separation efficiency is shown in Fig. 10 for an inlet consistency of 0.5 g/L and a split ratio of 1.8. The dashed line is the limiting value, η_s. For moderate flow rates, $\eta \simeq \eta_s$; while at flow rates of about 800 mL/min and larger, $\eta > \eta_s$. This means that the measured

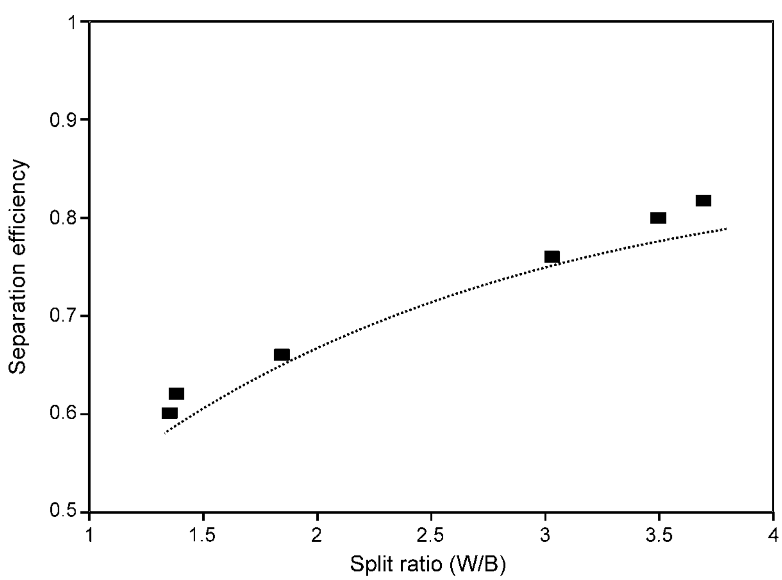

Figure 9. Separation efficiency (η) as a function of split ratio (W/B). $X_s = 0.5$ g/L and $S = 730$ mL/min. The dashed line is η_s calculated from Eq. (8).

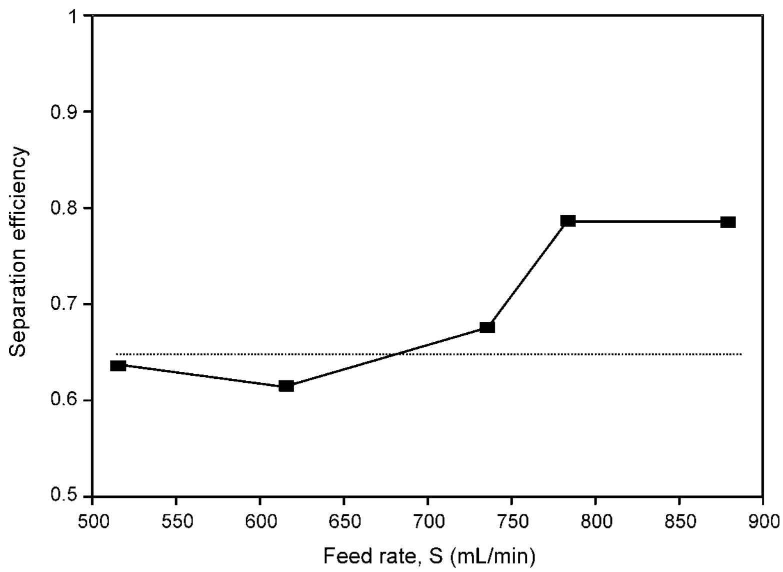

Figure 10. Separation efficiency (η) as a function of feed flow rate (S). $X_s = 0.5\,g/L$; $W/B = 1.8$. The dashed line is η_s.

top concentration of particles was larger than the particle concentration in the feed (C_s), which shows that particle generation occurred within the process vessel. This is similar to what was found in refs. 5 and 6 with the semibatch process when the operating flow rate was much higher than the minimum spouting flow rate. At high feed rates, more fiber deflocculation takes place and the surface of the pulp suspension rises higher and closer to the opposite wall of the vessel (see Fig. 5B). The released short fibers are easily carried in the top stream before being associated again with the fiber flocs resulting in an apparent increase in the separation efficiency.

Figure 11 shows the measured separation efficiency as a function of inlet consistency for a feed rate of 630 mL/min and split ratio of 2.1. The dashed line is the value of η_s. At low inlet consistency, $\eta \simeq \eta_s$; while at high inlet consistency, $\eta < \eta_s$. When the consistency is relatively high, the structure of the fiber flocs is more permanent and, hence, the liquid inside the flocs is not easily or rapidly exchanged with the bulk. In such a case, the residence time of the suspension within the vessel might not permit liquid exchange (which is accompanied by particle exchange). This decrease in liquid exchange in addition to the decrease in the external void fraction with increasing consistency, results in few particles able to follow the liquid streamlines,

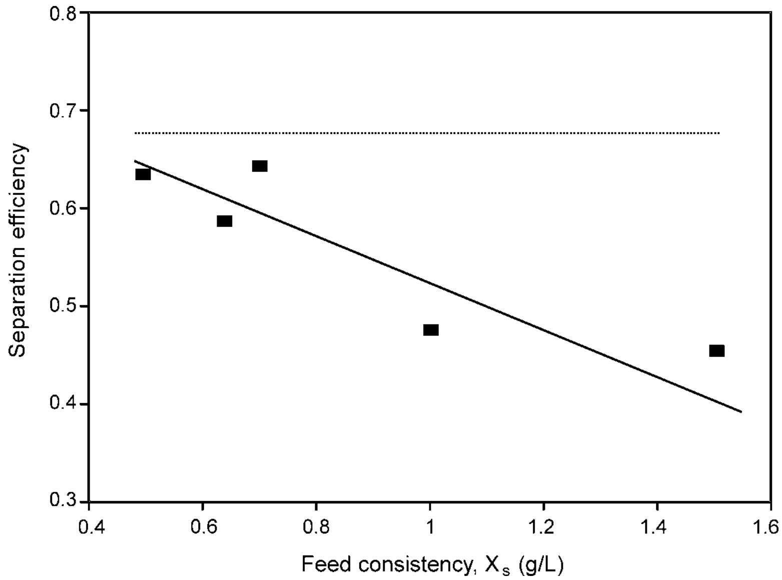

Figure 11. Separation efficiency (η) as a function of inlet consistency (X_s). S = 630 mL/min and W/B = 2.1. The dashed line is η_s.

and thus to be split between the two exit streams. More particles captured inside the flocs, left in the bottom stream than expected and consequently a separation efficiency less than η_s was obtained.

CONCLUSION

Particle fractionation by "elutriation-spouting" was achieved in a continuous operation in a wedge-like vessel. The process operates between lower and upper limits of the feed flow rate. The lower limit is independent of the split ratio; whereas the upper limit decreases somewhat with this ratio. There is a maximum inlet consistency above which the suspension phase expands and leaves in the top stream. For the geometry used in this study, the maximum consistency is about 0.15%, which is much lower than industrial pulp consistencies, which typically are 1%. It is likely that the maximum consistency can be increased by using taller vessels. The vessel height determines the maximum spouting velocity, which arises from a balance of upward flow and fiber floc sedimentation at height h. Since the velocity at the top of the diverging section scales as 1/h, it follows that the maximum spouting velocity increases linearly with vessel height. The minimum spouting velocity increases linearly with fiber consistency,[6] and spouting ceases when the minimum spouting velocity approaches the maximum one. Thus, it is expected that the maximum consistency increases with vessel height. Different vessel geometries might possibly also lead to operation at higher consistencies. This study can be regarded as a proof of the concept that separation is feasible.

The mechanism of separation is based on the exclusion of fibers from the top stream and the split of fines in the two outlet streams in proportion to the flow split ratio. The separation efficiency increases with increasing split ratio and decreases with increasing inlet consistency.

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