Effect of shear forces on fine particle retention

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ABSTRACT

An inverted cone is investigated as an alternate stirrer for a dynamic drainage jar. The cone is used to generate a known uniform shear field over the wire. Drainage rates are compared between the cone and the standard propeller stirrers. Both stirrers show a minimum in the drainage rate curve at 750 rpm and indicate filtercake formation even though the drainage rate is less than 100 mL in 30 seconds. The data for the propeller indicate filtercake formation at high stirring rates while the cone data do not. The retention curves for the two stirrers are similar in magnitude. However, at high stirring rates, the propeller and cone data show that retention goes to zero and a plateau, respectively. The influence of adding a retention aid is reported.

THE RETENTION OF MINERAL AND pulp fines is critical to papermaking and has been the subject of many studies *(1–4)*. Fines contribute beneficial properties to the paper in terms of optical and surface characteristics. Unretained fines pass into the white water system and present problems in recovery and loss to the mill effluent. Fines originate in the paper furnish from the fiber system and its processing such as refining, pumping, and washing. Fines occur as fiber fragments, detached fibrils, and parenchymatous plant cells or are added as a filler or pigment to improve optical properties. Fines are by definition, the particles that can pass a 200-mesh (75-µm) screen but are often much smaller, normally in the range of 0.2 to 2.5 µm *(3)*.

Fines are much smaller than the fibers and the wire and must be retained as a result of mechanical interception, adsorption, or other colloidal phenomena. Mechanical interception does not seem to be a critical mechanism for retention because of the small size of the fines compared to the fibers. However, gradients of fines in a fourdrinier machine may indicate a gradient of pore structure in the thickness direction as fines are caught in higher layers to form smaller and smaller pores. The natural electrostatic repulsion between negatively charged particles can be overcome with the addition of multivalent ions, polyelectrolytes, or other colloidal additives *(5)*. A fine balance persists in papermaking: Increasing the dose of a retention aid helps retention but damages formation. Retention problems are not always solved by adding more retention aid because of this balance. Retention is a complex relationship between process conditions (degree of refining, drainage rate, jet-wire ratio, and web speed), particle size distributions, pH level, electrical charge, ionic strength, flocculants, and coagulants added to the furnish. However, in general terms, retention is an interplay of hydrodynamic forces and nonhydrodynamic forces.

The Dynamic Drainage Jar (DDJ) was developed to study the effect of colloidal factors in isolation from that of hydromechanical factors to the largest possible extent *(1)*. Small drainage rates are used to avoid mat formation. A propeller-type stirrer is used to induce turbulence in the vessel and to help avoid mat formation. The intention is to get an idea of the first-pass retention, i.e., the retention before any mat is formed. No attempt is made to accurately control or determine the shear rate.

The DDJ is a popular tool for relating the effectiveness of retention aids. Little is known for this test in terms of the nature and magnitude of the shear forces. As a result, empirical variables, such as revolutions per minute (rpm) and stirring time, are used to describe the shear levels in this tester. Different shear rates are attained by changing the rotational speed of the propeller stirrer; usually retention decreases with increasing rotational speed. However, due to the shape of the propeller, high shear rates are produced in a small volume adjacent to the impeller tips, and small shear rates are produced near the vessel walls. In addition, the pressure field caused by the propeller causes most of the pulp suspension to pass through the center zone of the screen.

Several researchers have investigated the influence of shear rate or shear stress on retention. d'Incau *(6)* has made estimates of shear rates on the wet end of a high-speed paper machine; these have been used as a guide to the location of polymer retention aids. The estimates range from 10^2 s^{-1} for the table rolls and foils to 10^4–10^5 s^{-1} for the headbox slice or impeller tips. Shear rates for given operating conditions are not difficult to estimate. Tam Doo *et al.(7)* pointed out the importance of shear stress in these systems. The shear stress at the fiber wall should relate to retention. Hubbe *(8)* compared levels of shear stress relative to the ability of small particles to be retained. The shear stress on the fiber was estimated for different sec-

	Machine speed, m/min 305	610	760	1,000
Jet impingement	40	100	100	200
Table rolls	80	700	1,000	2,000
Foils	90	400	600	1,000
Headbox slice	30	80	100	200
Rectifier roll	50	100	200	300
Flow distributor	90	300	400	600
Pressure screen	10,000	10,000	10,000	10,000
Fan pump	20,000	20,000	20,000	20,000

I. Maximum shear stresses on fiber walls, $[\tau]_w$ (Pa), (7)

tions on the wet end for different operating conditions (**Table I**).

The purpose of this work is to attempt to improve the DDJ by using a cone-and-plate system to set up a uniform shear rate and shear stress for the fluid volume over the screen. In laminar flow, the shear rate set up in such a device is independent of the location. All of the fluid that reaches the screen has to "see" the shear field under the cone. This shear rate is calculated from the rotational speed and the geometry of the cone. In addition, the cone geometry should not pump fluid to a certain location; a more uniform drainage is expected. By using the cone in place of the stirrer, retention and drainage data are now obtained at a known shear rate instead of at a general stirring rate.

EXPERIMENTAL WORK

The geometry of the cone stirrer is shown in **Fig. 1.** The 30° angle was chosen to avoid constricting flow to the wire. One disadvantage of this large cone angle is the possibility of secondary flows. A small cone angle (less than 1°) would eliminate the secondary flows, but it would restrict flow to the wire. The secondary flows are weak and move outward from the cone surface, but they cause an error of less than 10% in torque predictions for these large cone angles *(9, 10)*. Therefore, a large-angle cone was chosen for these initial attempts to quantify the shear field during a retention experiment. The radius of 43.3 mm nearly fills the entire volume, which is 50 mm in radius. This radius was chosen to be as large as possible and yet not contact the walls of the jar or constrict drainage. With this radius, 75% of the wire area available for filtration will see the shear field. The cone should be mounted 5 mm above the wire to have the apparent cone tip touch the wire. As in conventional rheometers, this cone tip is removed to avoid mechanical contact between the screen and the cone. The cone was placed at this elevation with the help of a spacer; the cone was lowered to touch the spacer and clamped in place. The spacer was removed after clamping.

For small-angle cone-and-plate rheometers, the shear rate is constant everywhere in the gap and is given by:

$$\gamma = (2\pi\omega)/(\tan\alpha) \qquad (1)$$

where ω is the rotational rate (rpm) and α is the angle. The shear stress in the fluid is constant under the cone as is given by the above shear rate times the viscosity of the suspension. As the angle becomes smaller, higher shear rates can be obtained for the same rotational speeds. For any cone angle, the shear rate is dependent on position, and the equations are well known *(11)*. For a 30° angle, the error in Eq. 1 is less than 7% *(12)*.

The torque on the cone can be measured and recorded by a computer. The viscosity of the pulp suspension as drainage occurs could be recorded. The torque is given by:

$$T = (4\pi^2\mu\omega R^3)/(3\tan\alpha) \qquad (2)$$

where μ is the viscosity and R is the radius of the cone. This measurement was not the focus of this study, but it would give a direct measurement of the shear stresses in the fluid.

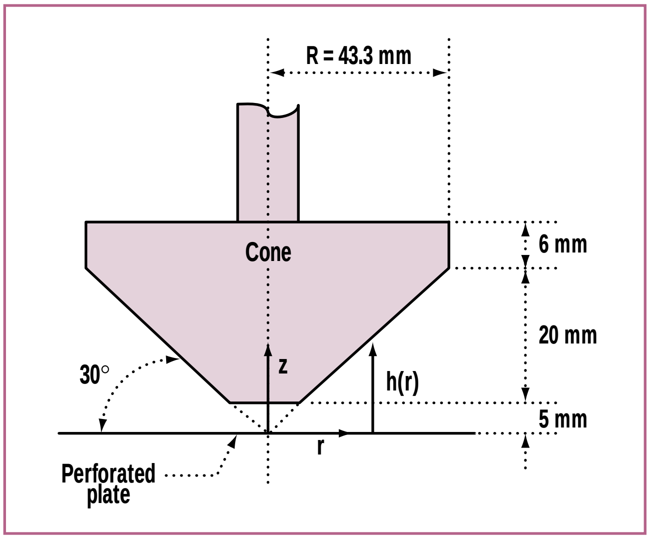
In a rotating liquid, the centrifugal forces cause a pressure gradient in the radial direction. At steady state, this pressure gradient must balance the gravity forces or the hydrostatic head; fluid is pushed to the walls of the container until the pressure gradient matches the height of the liquid at every radial position. The pressure gradient in the r direction and the resulting height profile are:

$$P = \rho g\{h_i + [(\omega^2\pi^2R^2)/g)] \times [(2r^2/R^2) - 1]\} \qquad (3)$$

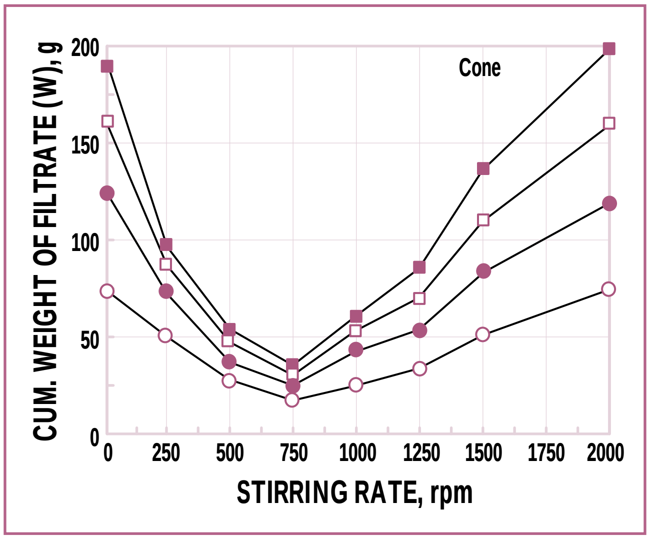
$$h = h_i + [\pi^2\omega^2R^2/g(2r^2/R^2) - 1)] \qquad (4)$$

where g is the acceleration of gravity *(11)*. When $\omega^2R^2/4g > h_i$, the liquid surface reaches the screen, the pressure goes to zero, and there will be no drainage through this region. With both stirrers, this shape of the free surface is seen as the liquid stock rotates above the screen.

TAPPI Test Method T 261 recommends collecting 80–100 mL of filtrate in 30 seconds. The solid content is determined by drying the filter paper in an oven for 2 hours at 105°C followed by a desiccator until its temperature reaches room temperature. The results for our trials



1. Schematic of the cone over the wire.



2. Cumulative weight of filtrate for different stirring rates with the cone. Curves from bottom to top are for 10, 20, 30, and 40 seconds, respectively.

had a high standard deviation between repeat trials. An alternate method was found to reduce the standard deviation: Dry the filter paper at 22°C and 50% moisture, and weigh at these conditions. The moisture content of fibers, fines, and filler at these conditions needs to be determined. Details of this method are reported by Arslan *(12)*. The total amount of fines was determined by wet screening by following TAPPI Test Method T 261.

The propeller stirrer is the device normally used in the DDJ, as described by TAPPI Test Method T 261. It has a diameter of 2 in. and is mounted 32 mm from the screen. The wire is a 200-mesh screen. Mat formation is not supposed to be important if the drainage rate is less than 100 mL in 30 seconds.

The drainage rates with the two stirrers were determined by collecting the filtrate every 10 seconds. The flow rate is not controlled by the stopper, which is fully open at time equal to zero. The collection is done manually by changing the collection vessel every 10 seconds. The weight of the filtrate is determined with a balance and is converted to volume using the density of the stock suspension.

The stock used in this study was a mixture of 80% groundwood and 20% clay. A fine grade of groundwood was used, typical of that produced for lightweight publication-grade papers (40 mL CSF). The standard propeller stirrer was used to estimate the fines content of the sample. The retention tests were performed at 0.5% consistency. The retention aid was a high-molecular-weight cat-ionic polymer (Percol 175), manufactured by Allied Colloids Corp. The zeta potential of the stock was about –20 m*V*.

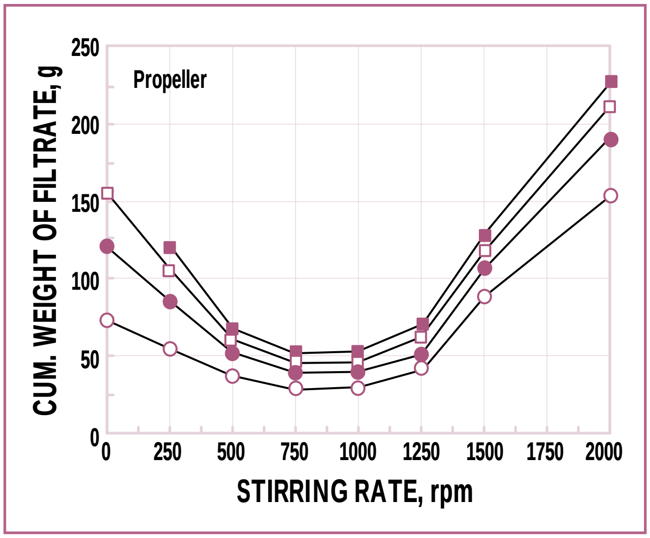
EXPERIMENTAL RESULTS

Drainage rates

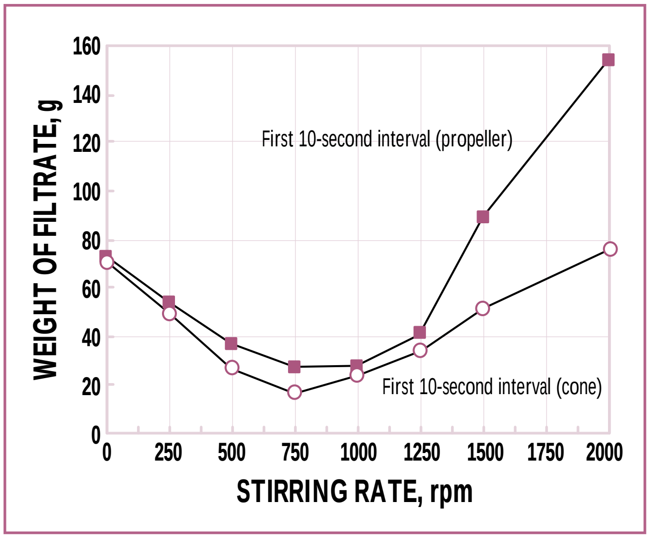
The cumulate weights of filtrate collected using the cone and the propeller stirrers are reported in **Figs. 2 and 3**, respectively. The data with the stirrer turned off are the same. The stirring rate for the cone can be converted into shear rate by using Eq. 1. Note that the shapes of the curves are very similar; the drainage rates go through a minimum at 750 rpm and then increase. The shape of the curve indicates that two opposing mechanisms are at work. Furthermore, the results suggest that a mat is forming on the wire; at any rotational speed, the rate of filtration decreases with time. This occurs even if we follow the guideline of collecting 100 mL in 30 seconds, as the results for 250–1250 rpm indicate.

The minimum in the curves can be caused by a number of different mechanisms. One mechanism may be related to mat formation; low or no stirring generates a loose or open mat, allowing high drainage rates. The increased shear rates form a compressed mat, reducing drainage. The larger stirring rates are enough to remove the mat from the wire. This mechanism does not explain the propeller data, because mat formation is evident even at 2000 rpm (the drainage rate decreases with time). Another possible mechanism deals with coagulation and flocculation. Low shear rates increase coagulation and resistance to filtration. Higher shear rates destroy flocs and increase filtration rates.

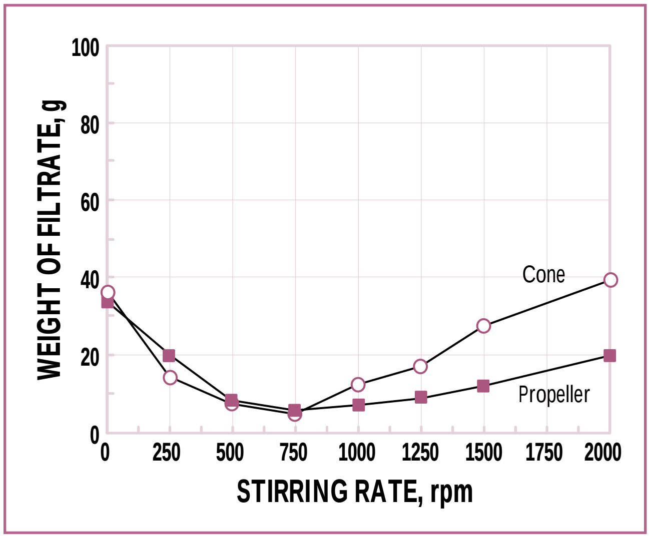
Another possible mechanism deals with the pressure field set up over the wire. At low shear rates, a low-pressure region forms at the center of the wire from centrifugal forces. This low pressure decreases drainage rates. At high stirring rates, a high-pressure region forms near the walls because of large liquid lev-



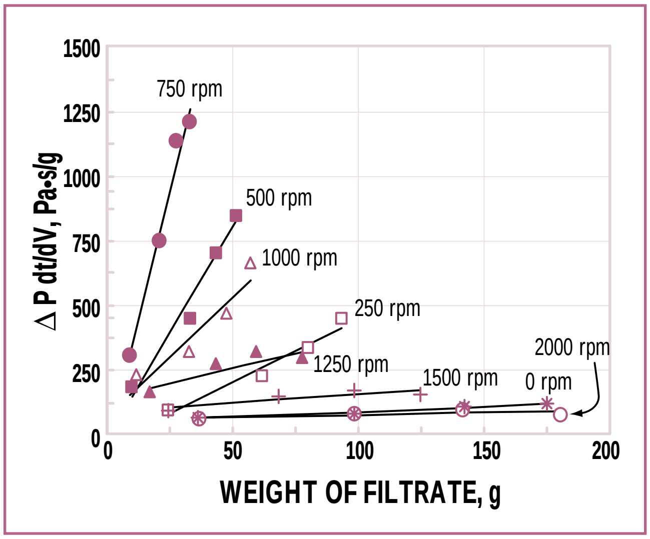
3. Same as Fig. 2 but with propeller. Curves from bottom to top are for 10, 20, 30, and 40 seconds, respectively.



4. Weight of filtrate collected the first 10 seconds for the cone and propeller.



5. Weight of filtrate collected the third 10-second time period for the cone and propeller.



6. Filtration curve for the cone. Slope of the line is related to specific cake resistance.

els in this region, and high flow rates are obtained through the large outside area of the wire. The total drainage rate through the wire is the integral of some resistance to flow k times the pressure drop:

$$\frac{dV}{dt} = 2\pi k \int_{R_0}^{R} P\, r\, dr \qquad (5)$$

where dV/dt is the volumetric drainage rate, and R_0 is either the center (zero) or the radial position where the pressure is zero, as determined from Eq. 3. If Eq. 3 is combined with Eq. 5, we obtain:

$$dV/dt = \pi\rho g K (R^2 - R_0^2)[h_i + (\pi^2\omega^2 R_0^2)/g] \qquad (6)$$

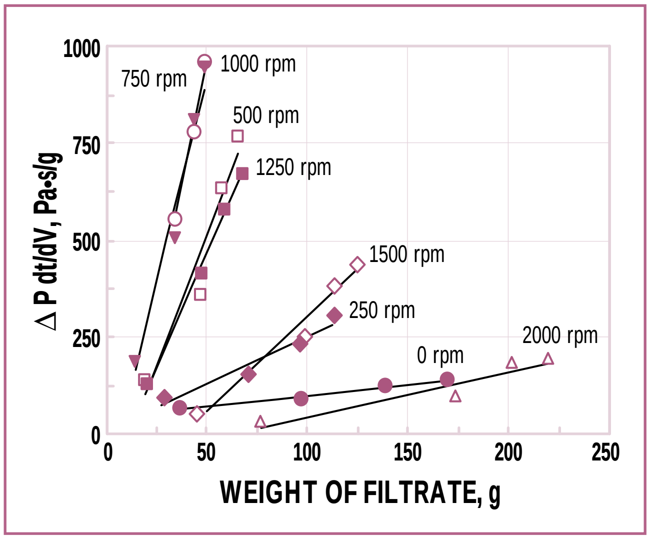
The value of R_0 is either zero or:

$$R_0 = \sqrt{(R^2/2) - [(h_i g)/(2\pi^2\omega^2)]} \qquad (7)$$

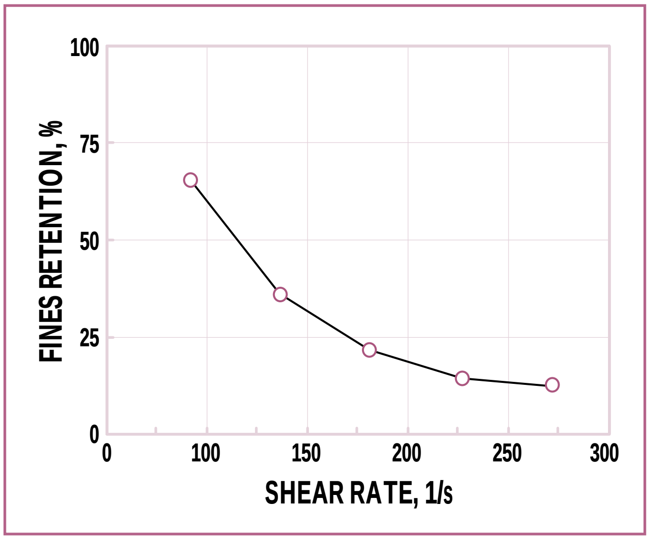
when the quantity under the square root is positive. For our conditions, this occurs at ω=300 rpm. When Eq. 7 is combined with Eq. 6, the result, valid for R_0 greater than zero is:

$$dV/dt = \pi\rho g K (R^2/2 + h_i g)/(2\pi\omega^2)\,[h_i + (\pi^2\omega^2/g)(R^2/2 - h_i g/2\pi^2\omega^2)] \qquad (8)$$

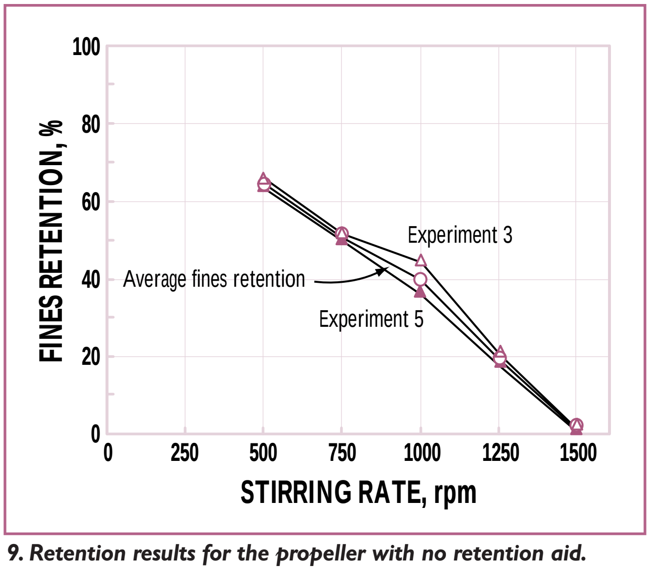
This equation shows the possible tradeoff with rotational speed. As the rotation increases, the area of the integral decreases (R_0 increases). In the limit of rapid rotation, the drainage rate should scale as ω^2. For our conditions, this does not give the



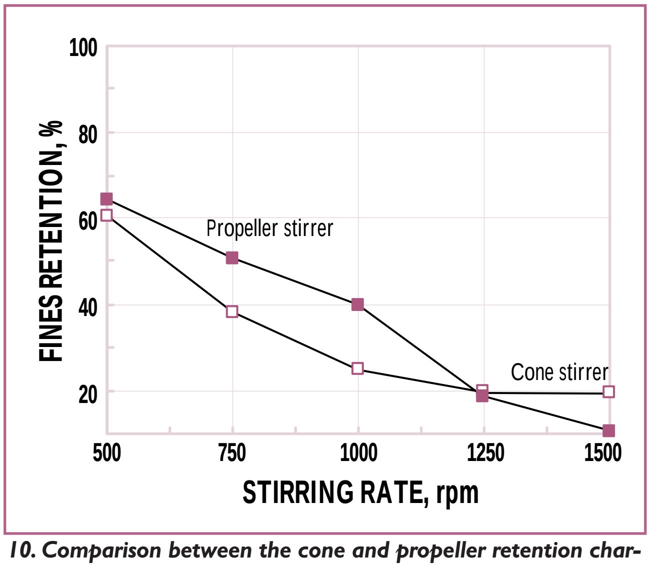
7. Filtration curve for the propeller. Slope of the line is related to the specific cake resistance.



8. Retention results for the cone with no retention aid. At high shear rates, retention reaches a plateau.



9. Retention results for the propeller with no retention aid. Retention goes to zero at high stirring rates.



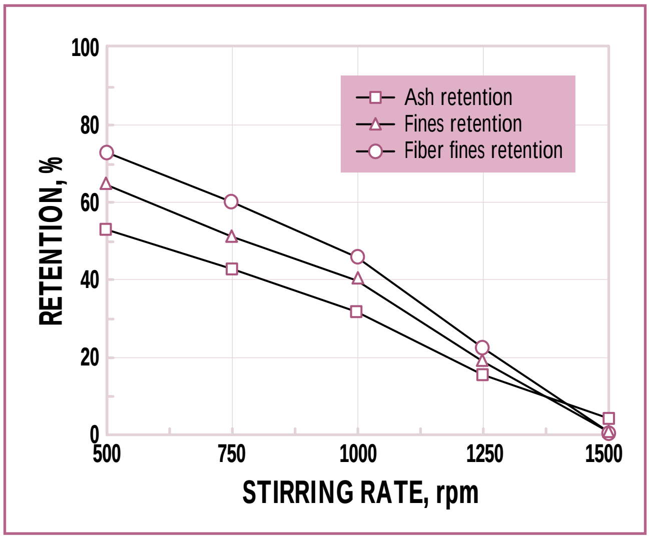
10. Comparison between the cone and propeller retention characteristics.

minimum at 750 rpm, but the cone or stirrer may disrupt the pressure field from Eq. 3.

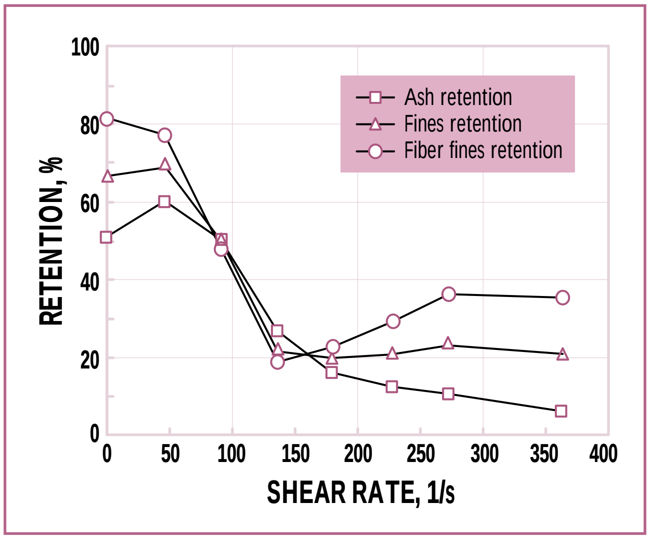
Figure 4 compares the weight of filtrate collected during the first 10 seconds for the two stirrers. Both show the same decrease with stirring rate, but the increase for the propeller after 1250 rpm is large compared to the cone. This must be caused by the jet of fluid impinging on the wire from the propeller. This pumping action is not present in the papermaking process and may influence retention.

After the first 10 seconds, the cone has the larger drainage rates at stirring rates greater than 1000 rpm. At the smaller stirring rates, there is little difference between the two. **Figure 5** compares the weight of filtrate collected for the third 10-second interval. The cone has larger drainage rates at the high stirring speeds. This result is likely caused by the lack of filtercake or mat formation with the cone; the drainage rate for the cone at the different time intervals is constant compared to the propeller. The rapid drainage rates for the propeller at high rotational speed must form a filtercake in the high-pressure regions that reduce the drainage rate for the next time intervals.

Basic filtration theory relates the flow rate to time given the pressure drop ΔP, the concentration of solids C_s, the retention coefficient R_1, the resistance of the wire R_m, the viscosity of the liquid phase μ, the area for



11. Ash, fiber, and total fines retention for propeller stirrer. No retention aid added.



12. Ash, fiber, and total fines retention for the cone. No retention aid added.

filtration A, and the specific filtercake resistances α_s. The relationship is:

$$dV/dt = A\Delta P/\{[(u\mu\alpha_s C_s V R_1/A) + R_m]\} \quad (9)$$

where t is time and V is the volume of filtrate. The specific cake resistance α_s can be expressed in terms of the void fraction of the mat and other constants:

$$\alpha_s = k_1(1 - \varepsilon)S_0^2/\rho_p\varepsilon^3 \quad (10)$$

If all the above quantities are constant, then the relationship is:

$$dt/dV = K_p V + B \quad (11)$$

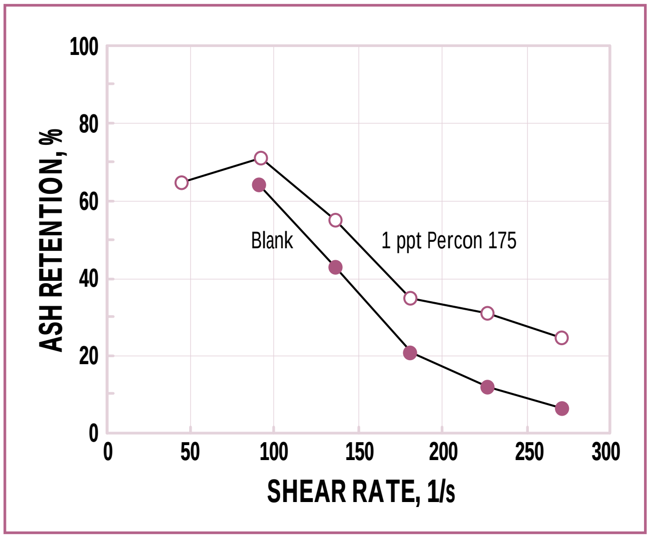
where K and B are constants. Standard filtration plots for the cone and the propeller are given in **Figs. 6 and 7**, respectively. At a constant rotational speed, the larger the slope of the line, the larger the specific cake resistance or the smaller the pressure drop for flow; the other quantities must be constant. For small slopes, either the reverse or no filtercake is forming. These figures indicate that a filtercake is forming, especially at stirring speeds near 750 rpm. However, for the cone at 1500 and 2000 rpm, the slope is very small. These results indicate that, for the cone, either a filtercake is not forming because of the shear field or that the filtercake that is formed has a high void fraction. The increased stirring speed for the propeller results in a drainage rate that decreases with time, a sign of filtercake formation.

Retention

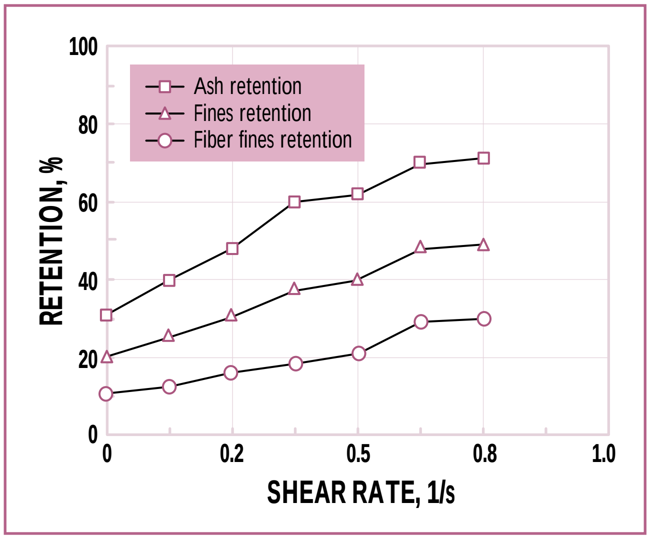
Figures 8 and 9 report the retention values with the stock and no retention aid for the cone and the propeller, respectively. The shear rate is reported for the cone instead of rpm, but 365 s^{-1} corresponds to 1500 rpm. Error bars and repeat experiments are given in Figs. 8 and 9, respectively, to demonstrate the accuracy of the procedure. Both stirrers show a decrease in retention with increasing stirring rates, and the values are comparable. However, the result trends at high stirring rates are different: The cone data tend to approach a steady value, while the propeller gives values that go to zero retention, as demonstrated in **Fig. 10.** This trend is true for fiber fines retention or ash retention, as shown in **Figs. 11 and 12**. The difference in the ash retention is not significant between the two stirrers; both go from around 60% to 5%. However, the difference between the fiber fines is large.

Retention going to a level value for the cone could be a result of all flocs being destroyed and only fines that are coagulated to fibers being retained. If this is the case, the test provides a clear indication of floc strength; the shear rate to obtain level retention values would predict the strength of the nonhydrodynamic forces holding the flocs together. From torque measurements, the floc strength can be estimated.

The reason for these different trends at high stirring rates is difficult to explain. Looking at the drainage rate data at high stirring rates, the propeller especially seems to form a filtercake, which would promote fiber fine retention. The cone does not indicate filtercake formation at high shear rates, but it gives high retention values compared to the propeller. A few different reasons may explain these results. The high stirring rates of the propeller may create fines by fracturing or chopping long fibers near the propeller tips. This increased number of fines in the sample would end up in the filtrate and show a decrease in retention (even possibly



13. Ash retention for the cone with 0.5 kg/metric ton retention aid.



14. Ash, fiber fines, and total fines retention with cone at 800 rpm (145 s^{-1}) for different dosage of retention aid.

KEYWORDS

Agitators, drainage jars, equipment, fines, retention, shear stress, stresses, test equipment, test facilities.

a negative retention). However, a clearance condition between the cone and the wire sufficiently close to generate fines is considered unlikely. Another possible reason for the low retention is the pumping action of the propeller; fines are washed out of the filtercake as fluid is pushed through it. The difference between the cone and the propeller may also be related to the length scale of shear or turbulence that they form and how this interacts with flocculation; the propeller may form very strong turbulent eddies that remove fines from fibers.

Influence of retention aid

The drainage rates are reduced by 7–20% at all stirring rates for the cone stirrer when 0.5 kg/metric ton (1 lb/ton) of the retention aid was added. No coagulant was used. Retention is improved for ash and fiber fines with the retention aid, especially at high stirring rates, as **Fig. 13** demonstrates. Once the shear rate is known, the interparticle force between the particles can be estimated based on Stokesian dynamics calculations; the hydrodynamic force to separate a fine from a fiber can be calculated *(13)*. Therefore, data such as those shown in Fig. 13 can potentially be used to characterize the interparticle force between the ash and fiber and between the fiber fine and fiber.

Figure 14 shows the increase in retention as the dose of the retention aid is increased at 800 rpm (145 s^{-1}). Ash and fiber fines show a steady increase. Flocculation through bridging and patching mechanisms likely scales linearly with polymer concentration. This may be the reason for the linear increase in retention.

CONCLUDING REMARKS

The results of an alternate cone stirrer in a Dynamic Drainage Jar are reported. The cone sets up a uniform shear field over the wire; most of the stock must pass through this shear field to approach and go through the wire. The magnitude of the shear field is calculated based on the cone angle and the stirring rate. Thus, retention may be related to the magnitude of the shear field or shear stress instead of the revolution rate of a stirrer.

The drainage rates and retention values for the cone are comparable with those obtained using a propeller stirrer. The cone stirrer shows increasing filler and fines retention with increasing dosage of retention aid at a fixed shear rate. However, drainage rates with the propeller indicate filtercake formation at high stirring rates, while the results with the cone do not. Retention values at high stirring rates go to zero for the propeller, but reach a plateau with the cone.

Unfortunately, the pumping action of the propeller and the nonuniform shear field generated by the propeller make the data from a standard Dynamic Drainage Jar difficult to interpret for fundamental studies on retention. Because the cone stirrer generates a known quantified shear rate, it can be used to estimate the interparticle potential for the papermaking system. In addition, the known shear rates should make it easier to scale laboratory results to the mill situation and predict paper machine performance. A troublesome problem in understanding the fundamental relationship of retention aids and shear rate is not having a single apparatus that gives a quantifiable measure of shear rate. The cone stirrer was developed to aid in solving this problem. **TJ**

Arslan was a graduate student, Bousfield is an associate professor, and Genco is a professor at the University of Maine, Department of Chemical Engineering, Orono, ME 04469-5737.

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