

Hydrodynamics of individual pulp fibers

SHELDON I. GREEN AND BRAD WONG

ABSTRACT: The hydrodynamic separation of different pulp fibers that occurs in a hydrocyclone has been studied in a rotating tank hydrodynamometer. The radial settling velocity is slightly greater for long fibers and is greater for fibers oriented at more than 45° to the tangential direction. The dependence of fiber radial velocity on fiber shape (curl and kink) is negligible. The average drag coefficient of softwood fibers was about twice that reported for model fibers, probably because the fibers have a fairly collapsed shape. The average drag coefficient of hardwood fibers was closer to that of the model fibers, perhaps because of their more nearly cylindrical structure. In general, there is a very large dispersion in the settling velocities of pulp fibers, thought to be caused by variations in fiber diameter and wet density.

Application: The Rotating Tank Hydrodynamometer (RTH) is a new device designed to measure the hydrodynamics of different pulp fibers, which may help to predict the separation of different pulp fibers in hydrocyclones.

During sheet formation, fibers with thin cell walls (earlywood) collapse readily into ribbons. Fibers with thick cell walls (latewood) resist collapse. With a small area of contact with other fibers, a fiber with a thick cell wall does not bond as strongly as a fiber with a thin cell wall. Separating fibers with different cell wall properties helps to tailor the furnish to the finished product.

One industrial approach for fractionating fibers is to use hydrocyclones [1]. In a hydrocyclone, the thick-walled fibers preferentially migrate to the reject stream, and thin-walled fibers move to the accept stream [2, 3]. To help predict the separation of different pulp fibers in hydrocyclones, a new device has been developed. The Rotating Tank Hydrodynamometer (RTH) works by measuring the hydrodynamics of different pulp fibers. Here, we describe the experimental measurement of the hydrodynamic characteristics of individual wood fibers under conditions simulating those in a real hydrocyclone.

BACKGROUND

Efforts have been made to model numerically the fiber motion in a hydrocyclone [4, 5]. The models involve first solving for the single-phase flow (pure water) in a hydrocyclone and then calculating the motion of “mock fibers” in the single-phase flow. Such calculations have required analysts to estimate the hydrodynamic characteristics of individual wood fibers—as cylinders or flexible linkages of spheres, for example. This esti-

mation process is prone to substantial error, which can be avoided through direct measurement of the fiber hydrodynamics.

Whether individual fibers, rather than fiber flocs, actually exist in hydrocyclones is not known; the fact that fiber fractionation can be achieved in a hydrocyclone suggests that individual fibers do exist. One may speculate that the intense shearing that occurs at the hydrocyclone inlet is sufficient to break up flocs in the suspension. However, in the majority of the hydrocyclone, where fiber fractionation occurs, the shearing is much weaker.

The Reynolds number of the flow around an individual pulp fiber is given by:

$$Re = (\rho_{\text{fluid}} D U) / \mu \quad (1)$$

where D is the fiber diameter, ρ_{fluid} is the fluid density, U is the fiber velocity relative to the fluid, and μ is the fluid viscosity. Typical Reynolds numbers of fiber flow in a hydrocyclone are in the range of 0.05–2, depending on the hydrocyclone characteristics, the exact location in the hydrocyclone, and the fiber characteristics [6].

No one has previously measured the hydrodynamics of pulp fibers at Reynolds numbers of order 1. Others have analytically and experimentally determined the drag on objects similar to pulp fibers. A rigid two-dimensional circular cylinder is similar to a pulp fiber. Lamb derived a theoretical equation to predict the drag of such a cylinder placed in a stream of fluid with its axis normal to the flow [7]. He

showed that the drag coefficient is given by

$$C_D = \frac{8\pi}{Re(2.002 - \ln(Re))} \quad (2)$$

where

$$C_D = \frac{F_D}{0.5 \rho_{\text{fluid}} U^2 L D} \quad (3)$$

In these expressions, L is the cylinder length (which approaches infinity in the case of a two-dimensional cylinder), and F_D is the drag on the cylinder.

Cox considered the creeping flow around a long slender solid body that may or may not be straight [8]. Cox developed a general theory to find the hydrodynamic force exerted on such body when it is placed with its axis perpendicular to a uniform flow. He found that

$$C_D = \frac{8\pi}{Re(\ln(2L/D) + 0.193)} \quad (4)$$

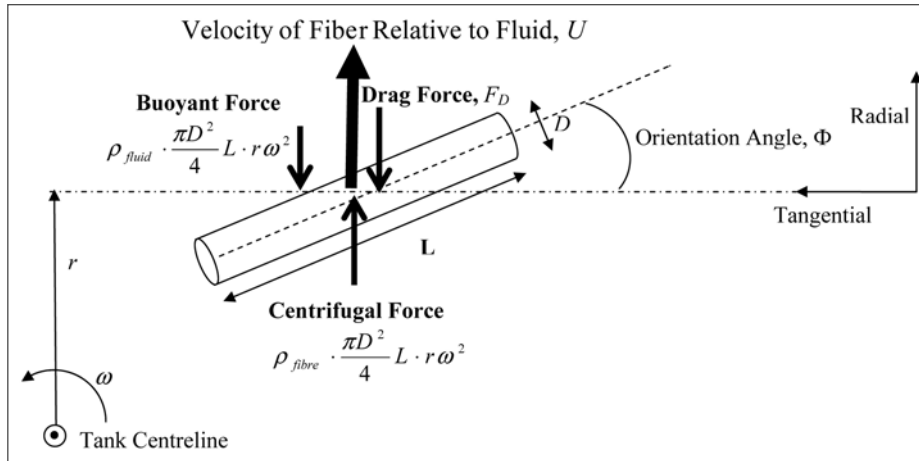
Aidun pioneered the experimental study of the hydrodynamics of fibers [9]. He carried out free settling experiments with different types of fibers (nylon, rayon, dacron, orlon, and cotton) and determined a general expression to predict the drag on fibers for aspect ratios $L/D > 90$:

$$C_D = 10.4 / Re^{0.738} \quad (5)$$

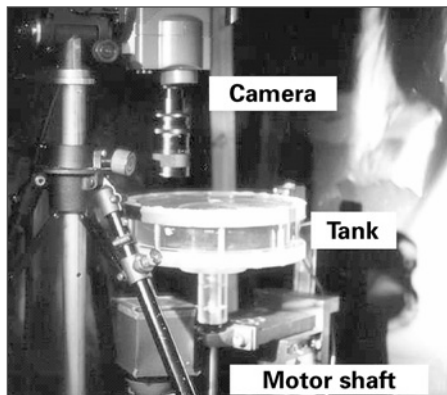
for $0.007 < Re < 2$.

The Rotating Tank Hydrodynamometer (RTH) was developed to study experimentally the hydrodynamics of pulp fibers at the Reynolds numbers typ-

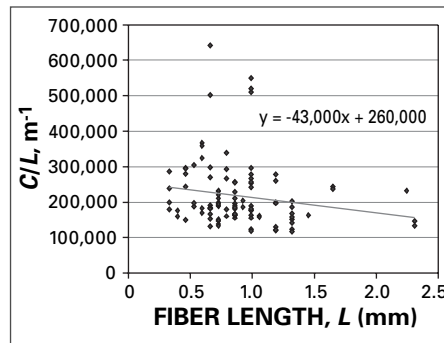
FIBER PROPERTIES



1. Diagram of forces acting on a fiber. The fiber is a distance r away from the center of the tank and has diameter D , length L , and average density ρ_{fiber} . The fiber moves relative to the fluid in the radial direction at a velocity U , the radial settling velocity. The orientation of the fiber in the plane perpendicular to the tank rotation axis is given by Φ . The orientation out of the plane of rotation was not measured.



2. Rotating Tank Hydrodynamometer.



3. Creeping flow drag coefficient per unit length, C/L , versus fiber length, L , for hardwood kraft fibers.

	Length in RTH, mm	Measured diameter, μm	Aspect ratio, L/D
Softwood kraft	1.91	33.3	57
Softwood TMP	1.66	33.8	49
Hardwood kraft	0.87	20.0	44
Hardwood CTMP	0.85	22.3	38

I. Summary of average pulp fiber properties.

ical of hydrocyclones [10]. The basic concept of the RTH is to develop a simple solid body rotation in fluid motion. Once this solid body rotation is developed, fibers or other objects for testing can be inserted in the flow to observe their motion. Since the flow field is known, measurements of the fiber motion may be used to derive the fiber hydrodynamic characteristics. In particular, a fiber inside the rotating tank spinning at rotation rate ω is subject to a centrifugal force, a drag force, and a buoyant force (Fig. 1).

The radial equation of motion of a fiber in the rotating tank will be exactly the same as during gravitational settling, except that the gravitational acceleration is replaced by the centrifugal acceleration:

$$\rho_{\text{fiber}} \cdot \frac{\pi D^2}{4} L \frac{d^2 r}{dt^2} = r \omega^2 \rho_{\text{fiber}} \frac{\pi D^2}{4} L - C \mu D \left(\frac{dr}{dt} \right) - r \omega^2 \rho_{\text{fluid}} \frac{\pi D^2}{4} L \quad (6)$$

where

ρ_{fiber} = average fiber wet density

L = fiber length

D = fiber diameter

r = radial distance of the fiber from the axis of rotation

C = creeping flow drag coefficient.

The average fiber wet density is the average over the cell wall and any fluid-filled cell lumen. C is given by $F_D/(\mu D U)$, where $U = dr/dt$ is the radial velocity of the fiber [12].

Note that the creeping flow drag coefficient, not the conventional drag coefficient, is used in Eq. 6. The rationale for this choice is that at high Reynolds numbers inertial forces are dominant and, as a consequence, the drag coefficient, C_D , is nearly independent of Re . In contrast, at low Reynolds numbers viscous forces, not inertial forces, are dominant, and therefore the creeping flow drag coefficient is nearly independent of Reynolds number. The relationship between the creeping flow drag coefficient and the more familiar inertial flow drag coefficient is:

$$C = \frac{C_D U L \rho_{\text{fluid}}}{2 \mu} = (C_D / 2) \cdot Re \cdot (L / D) \quad (7)$$

In Eq. 6, the left-hand side represents the inertial force acting on the fiber, the first term on the right side represents the centripetal acceleration of the fiber, the second term represents the fiber drag force, and the third term represents the net hydrostatic pressure force (equivalent to a radial buoyant force) acting on the fiber. One may show that during testing in the tank, the fiber acceleration term is three orders of magnitude less than the other terms. The equation of motion of the fiber can therefore be rewritten to express the creeping flow drag coefficient at “radial settling velocity” as:

$$C = \frac{\pi \cdot D \cdot L \cdot (\rho_{\text{fiber}} - \rho_{\text{fluid}}) r \cdot \omega^2}{4 \cdot \mu \cdot U} \quad (8)$$

RTH

The RTH is a cylindrical, transparent container driven by an electric motor. The rotating tank is constructed from two circular plexiglas plates and a plexiglas tube, as illustrated in Fig. 2. The tank internal diameter is 25.4 cm, and its internal height is 4.4 cm.

The tank is filled with water, and fibers are placed in the tank through a small hole drilled in the center of the tank. A high-speed video camera captures the motion of the fibers as they are flung to the exterior of the tank by the centrifugal forces. Further details of the RTH were given earlier [10].

The RTH has been validated by testing objects (glass spheres, copper wires, and nylon fibers) of known drag in the tank [10]. Glass spheres with diameters of 2 mm and 3 mm were tested in the RTH when it was filled with pure glycerin. The results showed good agreement with Stokes Law (within 2% and within 15%, respectively, for the two sphere sizes).

Similarly, long copper wire with a uniform diameter of 0.254 mm was cut into pieces 6 mm long to give an aspect ratio of 23. Wire pieces with higher aspect ratios were not used because their length would cause excessive interactions with the RTH walls. The least squares fitting of the results showed agreement within 4.4% of Cox's prediction for 3-D cylinders [8].

Dyed nylon fibers, 8 denier thick and 1 mm long, were tested in the RTH filled with distilled water. The agreement with the Aidun's experimental results on similar fibers was within 5% for most Reynolds numbers.

EXPERIMENTAL PROCEDURES

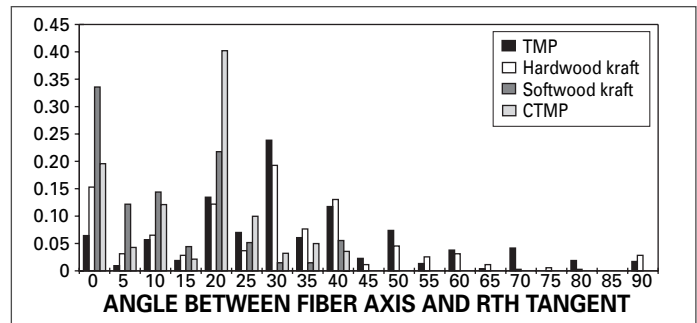
After the validation of the RTH, measurements were carried out on unrefined bleached hardwood kraft, bleached softwood kraft, hardwood chemi-thermomechanical pulp (CTMP), and softwood thermomechanical pulp (TMP). The pulp fibers tested were produced from dry pulp mat. Pieces of the dry mat were soaked in distilled water for five hours. All edge fibers were removed by hand. The pulp mat was then heated in a hot water bath with a temperature of 90°C for 45 min before a 45 min disintegration at 700 rpm in a laboratory repulper. All pulp fibers tested were prepared in this manner.

A sample size of about 200 was used for each type of pulp fiber during RTH testing. Pulp fibers were individually introduced into the RTH. The speeds and lengths were measured, and their shapes were recorded (straight, curled, or kinked).

A Fiber Quality Analyzer (FQA) was used to measure the average length of the fibers in each type of pulp. For each type, the FQA measured in excess of 5000 fibers.

The FQA measurements showed that the RTH fibers were not sampled completely randomly; owing to the relative ease with which longer fibers could be measured, the distribution of fibers tested in the RTH was biased to long fibers. For example, the FQA determined that the mean fiber length of the softwood TMP fibers was 1.26 mm, whereas the average fiber length tested in the RTH was 1.66 mm. Similarly, FQA measurements showed an average CTMP fiber length of 0.56 mm, whereas the average length of the fibers tested in the RTH was 0.85 mm. The equivalent figures for hardwood kraft were 0.79 mm (FQA) vs. 0.87 mm (RTH), and the values for softwood kraft were 1.90 mm (FQA) vs. 1.91 mm (RTH).

The average wet density of pulp fibers was estimated by means of a buoyancy sampling method. We prepared five different densities of a mixture of sugar and water. A small amount of pulp fibers was introduced to each 1 L container of sugar solution. The solution was gently stirred to spread the fibers evenly. The fibers were allowed to settle for one minute. The number of fibers suspended in the body of the fluid was compared with



4. Orientation (Φ) histogram of all pulp fibers.

the number of fibers that floated on top or had sunk to the bottom. The average wet density of the fibers was determined by the container with the highest percentage of neutrally buoyant fibers.

The average wet density measured in this way was found for all types of fiber to be $1200 \pm 50 \text{ kg/m}^3$. In a particular density of fluid, some fibers of one type (such as softwood kraft fibers) would float, whereas other fibers of the same type would sink. This observation indicates that wood fibers have a range of wet densities, not a uniform wet density.

Many fibers were spread on a glass microscope slide, and a microscope was used to measure the "diameter" of a representative sample of the fibers. We assume that the fiber lumen would be collapsed when the fibers are viewed on a microscope slide, owing to the force applied by the cover slip. This assumption is likely to be accurate for thin-walled fibers and is even fairly accurate for thick-walled fibers [11]. We assume that, when the fiber is floating in suspension, its lumen is filled with water and the fiber has a roughly cylindrical shape. Consequently, its "true diameter" in suspension is: true diameter = $(2/\pi) \times \text{measured diameter}$. Table I summarizes the mean fiber properties.

RESULTS AND DISCUSSION

Fiber length

To study the effect of fiber length on the creeping flow drag coefficient, we observed 200 individual fibers of each type of pulp in the RTH. Figure 3 shows a typical plot of the creeping flow drag coefficient per unit length, C/L , versus fiber length L . For extremely long fibers, one would expect the drag to increase almost linearly with the length, with C/L thus being constant.

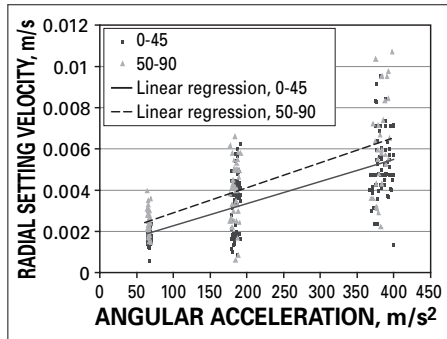
For hardwood kraft and CTMP pulp, C/L appears to decrease somewhat with increasing L . The effect is fairly small, however. As the linear regression curve shows, the creeping flow drag coefficient decreases by 24% when the fiber length increases from 0.5 mm to 1.5 mm.

For softwood kraft and TMP, C/L shows an even weaker dependence on fiber length. There is about a 10% reduction in C/L when L varies from 1 mm to 3 mm. These results are reasonably close to the 20% drop in C/L predicted by Cox's theory, when the length-to-diameter ratio of a cylinder is increased from 30 to 90.

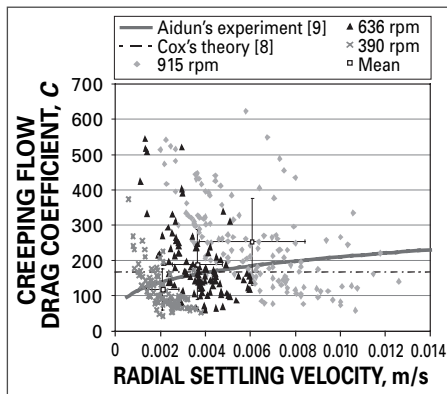
Fiber orientation

Like the copper wires and nylon fibers tested previously [10], all pulp fibers were observed to orient themselves fairly randomly in the RTH, depending on the angle at which they were introduced into the tank. The fibers largely maintain their origi-

FIBER PROPERTIES



5. Effect of fiber orientation on the radial settling velocity of hardwood CTMP. Fibers with axes nearly parallel to the RTH tangent ($0^\circ \leq \Phi \leq 45^\circ$) moved less rapidly than did those almost perpendicular to the RTH tangent ($50^\circ \leq \Phi \leq 90^\circ$).

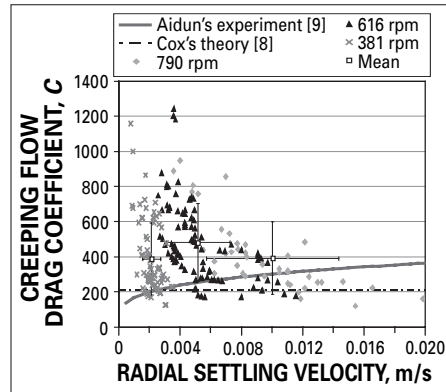


8. The hydrodynamic properties of hardwood kraft.

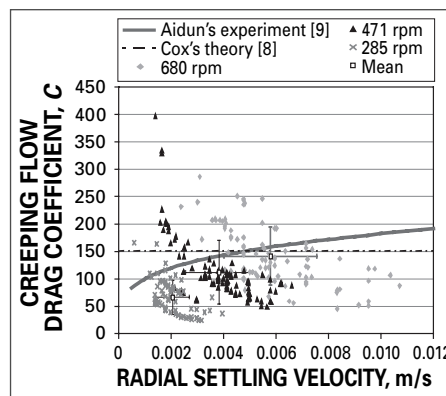
nal orientation throughout the settling process. In contrast with the assumption made in some models, most fibers do not orient themselves with their long axis perpendicular to the direction of radial motion. The fiber orientation can be anything from purely perpendicular to purely parallel to the direction of radial motion.

As illustrated in Fig. 4, most of the fibers had an orientation angle Φ smaller than 45° , presumably as a result of how they were introduced into the tank. Fibers having large angles settled faster on average than those oriented at smaller angles (Fig. 5), which is indicative of their lower drag coefficient. The variation with angle is such that fibers almost parallel to the radius vector move about 30% faster on average than those nearly perpendicular to the radius vector.

This result is in qualitative agreement with creeping flow theory [12]. However, creeping flow theory predicts



6. The hydrodynamic properties of softwood kraft. (A settling velocity of 0.01 m/s corresponds with a fiber-diameter-based Reynolds number of about 0.4.)



9. The hydrodynamic properties of hardwood CTMP.

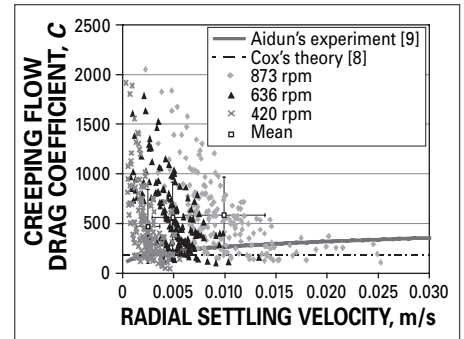
a doubling of fiber speed. The difference may be attributed to the fact that creeping flow theory is officially applicable only to rigid, straight cylinders of uniform diameter. Pulp fibers are not rigid, straight, or uniform in diameter.

Fiber shape

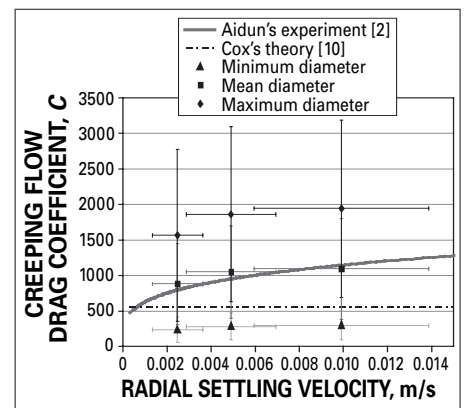
Most of the fibers captured by the high-speed camera did not take the catenary shape described by Aidun [9]. Rather, perhaps owing to their relatively great mechanical stiffness, the fibers tended to have about the same shape as they would have had without the applied centrifugal force. Fiber curl or kink was not found to have a statistically significant effect on the settling velocity.

Comparison with results of Aidun and Cox

In Fig. 6, where C is plotted against the radial settling velocity for softwood kraft fibers, the raw data are shown by symbols. The cross at each RTH condition indicates the mean and standard deviation.



7. The hydrodynamic properties of softwood TMP.



10. Influence of assumed fiber diameter on C (softwood TMP). (The squares represent the mean and standard deviations of the values of C and V at each of the three RTH speeds. For the squares, diamonds, and triangles, respectively, the fibers tested are assumed to have average, maximum, and minimum fiber diameters.)

tion for the fiber velocity and for the creeping flow drag coefficient. For comparison purposes, the experimental results of Aidun and the theoretical results of Cox are also shown. The means at each RTH rotation rate of the experimental results are on average 1.6 times those of Aidun's experimental results. The experimental value of C is on average 2.0 times that predicted by Cox's theory.

Figure 7 shows a similar plot for the hydrodynamic properties of softwood TMP. On average, the results are about 2.4 times those of Aidun and 2.9 times those of Cox. For the softwood kraft and TMP, the fiber results presented here are much more consistent with one another than is either with the results of Aidun and Cox. To be explicit, the mean value of C averaged over all the TMP fibers was 543, which is only 22% different from the

average value of C (422) of the softwood kraft fibers.

Figure 8 shows the same kind of plot for the hydrodynamic properties of hardwood kraft. On average, the experimental C values are a factor of 1.05 times those of Aidun and 1.00 times the theoretical values of Cox. The close agreement with the Aidun and Cox results is somewhat serendipitous in view of both the large scatter in the data and the fact that C increases significantly with increasing settling velocity.

Figure 9 shows the hydrodynamic properties of hardwood CTMP. The average creeping flow drag coefficient of the CTMP fibers is a factor of 0.76 of the results of Aidun and a factor of 0.70 of the results predicted by Cox. Hardwood kraft fibers on average have a 44% higher C than that of CTMP fibers.

All pulp samples tested, including this hardwood CTMP, have an increasing value of C as a function of the settling velocity. This finding is in agreement with the experiments conducted by Aidun on uniform cylindrical synthetic fibers. The reasons for this dependence of C on velocity is thought to be that there is a Reynolds number dependence of the flow around a fiber—even at these low Reynolds numbers (on the order of 0.2). This Reynolds number dependence suggests that even lower values of C would be measured at still slower settling velocities, but such lower velocities could not be achieved in the RTH apparatus.

Experimental variation in C from fiber to fiber

There are many reasons for the large experimental variation in drag coefficient from fiber to fiber. Probably the most important of these is that the pulp fibers vary in diameter. The effect of diameter variation is best illustrated by means of a sensitivity analysis.

The creeping flow drag coefficients were recalculated based on the minimum, mean, and maximum fiber diameters measured under an electron microscope. As shown in Fig. 10 for TMP, C increases by a factor of 6 from the minimum measured diameter of 9.1 μm to the maximum diameter of 60.1 μm . Other pulp fibers show similar spreads—a factor of 4 for hardwood kraft, a factor of 4 for CTMP, and a factor of 5 for softwood kraft. This effect explains a large part of the variation in drag coefficients

from fiber to fiber, as observed experimentally. Because diameter has such a substantial effect, the diameter of each fiber should be measured during settling to obtain more accurate values of C . However, it is not possible to make this measurement with the RTH equipment.

The wet densities of individual fibers were not measured; only the average density was measured (1200 kg/m^3). A sensitivity analysis shows that the drag coefficient is quite sensitive to the object density. As shown in Fig. 11, reducing the assumed fiber wet density from 1250 kg/m^3 to 1150 kg/m^3 (an 8% decrease) causes C to decrease by about 40%. Therefore, any variation in wet density from fiber to fiber would also lead to a large variation in the value of C .

Yet another reason for the spread in results is the varied orientation of fibers in the tank. As we showed in Fig. 6, the orientation significantly influences the radial settling velocity of fibers.

CONCLUSIONS

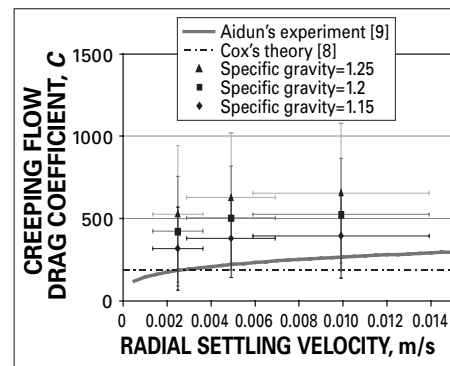
The Rotating Tank Hydrodynamometer has been developed and was previously validated by testing it on spheres, copper wires, and nylon fibers [10]. The testing of hardwood kraft and CTMP fibers as well as softwood kraft and TMP fibers gave rise to several observations.

The orientation of a fiber in the tank depends strongly on its initial orientation. In contrast with a widely used assumption, most fibers do not orient themselves with their long axes perpendicular to the direction of radial motion. The fiber orientation can be anything from purely perpendicular to purely parallel to the direction of radial motion, with the majority of the fibers oriented in the range of 0° to 40° from the perpendicular.

Fibers do not rotate appreciably, regardless of their orientation. Rather, they maintain their approximate orientation during the entire radial settling process in the rotating tank.

The radial settling velocity of pulp fibers is a function of their orientation. Fibers traveling with their axis nearly parallel to their relative velocity vector settle more rapidly (on the order of 30% faster) than those that are nearly perpendicular to the velocity vector.

The radial settling velocity increases somewhat with fiber length, but the



11. Influence of assumed fiber wet density on C (softwood TMP). (The squares represent the means and standard deviations of the values of C and V at each of the three RTH speeds. For the squares, diamonds, and triangles, respectively, the fibers tested are assumed to have wet densities of 1200 kg/m^3 , 1250 kg/m^3 , and 1150 kg/m^3 .)

effect is quite small (10% to 15%). This small effect may be caused by the fact that fiber length may be correlated with fiber diameter and wall thickness.

The average drag coefficient measured on softwood kraft and softwood TMP fibers is about double that measured by Aidun [9]. This difference is thought to arise because the fibers are highly noncylindrical. Much better agreement with Aidun's results is obtained if the fibers are assumed to have a rectangular, not a circular, cross-section [13].

The average drag coefficients of hardwood kraft (5% greater) and CTMP fibers (24% less) are much closer to those measured by Aidun. The better agreement with Aidun's results, compared with the softwood fibers, may be attributable to the simpler, more nearly cylindrical structure of the hardwood fibers.

The hardwood fibers have an increasing creeping flow drag coefficient with increasing settling velocity, which parallels the increase measured by Aidun. The softwood fibers show no obvious variation in drag coefficient with settling velocity.

There is a very large dispersion in the settling velocities and drag coefficients of pulp fibers. This dispersion is thought to arise from fiber-to-fiber variations in length, shape, orientation, diameter, and wet density. Fiber diameter and wet density were not measured for the individual fibers tested in the RTH. In follow-up research, these quantities were meas-

FIBER PROPERTIES

ured, and the incorporation of the measurements reduced the drag coefficient dispersion [13]. **TJ**

ACKNOWLEDGEMENT

The authors gratefully acknowledge the financial support of NSERC through its Woodpulp Networks of Centres of Excellence as well as the financial support of AstenJohnson, Inc. Peter Taylor of Paprican contributed substantially to this project through his work designing and fabricating the RTH.

LITERATURE CITED

1. Kure, K.A., Dahlqvist, G., Ekstrom, J., and Helle, T., *Nordic Pulp Paper Res. J.* 14(2): 100–105(1999).
2. Paavilainen, L., *APPITA J.* 45(5): 319(1992).
3. Li, M., Johnson, R., Xu, L., *et al.*, *J. Pulp Paper Sci.* 25(8): 299(1999).
4. Sevilla, E.M., and Branion, R., *J. Pulp Paper Sci.* 23(2): J85(1997).
5. Statie, E.C., Salcudean, M.E., and Gartshore, I.S., *Filtration and Separation* 38(6): 36(2001).
6. Hill, R. J., Koch, D.L., and Ladd, A.J.C., *J. Fluid Mechanics* 448: 213(2001).
7. Lamb, H., *Hydrodynamics*, 6th edn., Dover Publications, New York, 1932.
8. Cox, R.G., *J. Fluid Mechanics* 44(4): 791(1970).
9. Aidun, A.R., "Free settling of fibers in fluids," Ph.D. thesis, Dept. of Chemical Engineering, Syracuse University, New York, 1956.
10. Wong, T.B., and Green, S.I., *TAPPI J.* 2(3): 19(2003).
11. Jang, H.F., and Seth, R.F., *TAPPI J.* 81(5): 167(1998).
12. Happel, J., and Brenner, H., *Low Reynolds Number Hydrodynamics*, Prentice-Hall, New Jersey, 1965.
13. Green, S.I., "Pulp Fiber Drag Coefficient," submitted to the *APPITA J.*, Sept. 2004.

Received: September 22, 2004

Revised: January 10, 2005

Accepted: January 11, 2005

This paper is also published on TAPPI's web site <www.tappi.org> and summarized in the April *Solutions! for People, Processes and Paper* magazine (Vol. 88 No. 4).

INSIGHTS FROM THE AUTHORS

We chose this topic of research to try to get some experimental basis for predicting the motion of pulp fibers in a hydrocyclone. This paper supports two other pieces of research along the same lines. One, also published in *TAPPI JOURNAL*, concerns the development of the Rotating Tank Hydrodynamometer. The second involves studies of individual fiber morphology and links that morphology to the fiber hydrodynamics.

This research lays the groundwork for the development of superior hydrocyclone simulation programs. Ultimately, mills will benefit if hydrocyclone manufacturers use the results of this work to design superior products.

Observing small pulp fibers moving rapidly required some careful synchronization of the turntable to the strobe light and the elimination of all background

light sources. The wide variability in fiber drag coefficient was initially surprising, until one considers the enormous variation in fiber characteristics (length, diameter, wall thickness, density, and shape).

The next steps are to determine the reasons for the large spread in fiber drag and then to incorporate this knowledge into a superior simulation for hydrocyclone fluid dynamics.

Green and Wong are with the Dept. of Mechanical Engineering, University of British Columbia, 2324 Main Mall, Vancouver, BC, V6T 1Z4, Canada. Email Green at green@mech.ubc.ca.



Green



Wong