A Visual Study of Pulp Floc Dispersion Mechanisms

The dispersion of artificially produced softwood pulp flocs in controlled, plane, turbulent Couette flow was studied by using both monocular and stereoscopic film techniques. The mechanisms of controlled floc formation and of dispersion are proposed. For the latter, two mechanisms were observed, one global that involves deformation, breaking, and fragmentation, and one local that involves surface erosion. The effect of the flow field stress level on the time and rate of dispersion is presented.

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Introduction

The objectives of this study are to add to our understanding of fiber-fluid interactions in order to help develop flow management concepts that would provide improved control of fiber-fluid systems. Of particular interest is the breakup of fiber flocs in a turbulent flow. In the final stages of papermaking the pulp suspension is dispersed in a headbox and then forced through a sluice onto a moving screen where the water drains and the sheet forms. It is important that the fiber be uniformly distributed in the suspension during this operation. Flocculated fiber aggregates, called flocs, result in nonuniformity in the sheet and may cause sheet breakup during processing. Regions of voids are even more detrimental, forming pinholes and resulting in tears.

While shear gradients in the flow causes fibers to collide, entangle, and form flocs, they also disrupt the structure of the flocs. Hence, the process is a reversible one and an equilibrium state (where the formation rate equals the rupture rate) may exist. The general belief is that high-intensity and fine-scale turbulence would enhance deflocculation and would thus shift the equilibrium toward a lower degree of flocculation.

Instead of studying the flocculation-dispersion process by a statistical approach as most of the previous investigations have done, this study focuses on the dispersion mechanism of single flocs. A visual technique is employed because of its success with the coherent structures in turbulence studies. By observing the dynamics of the dispersion process, insight into the interactions of the fiber and fluid system are obtained. With the use of single flocs instead of a suspension, the complication of flocculation is eliminated. It is necessary to know first what is required to break and to disperse a highly entangled fiber floc without the interference of fibers in a suspension before going to the next step of studying how flocculation affects dispersion.

Robertson and Mason (1957) reported reduction in a flocculation index in the turbulent flow regime. Parker (1961) found that higher turbulence resulted in smaller flocs. However, Wrist (1962) indicated that doubling the velocity only produced a slight decrease in the number of large flocs. The intensity of turbulence may change the intensity of flocculation but not the scale of the flocs. The dominant floc size appeared to lie between one and two times the fiber length. Andersson's (1966) model predicted that rupture probability increases with increasing variance of velocity fluctuation and floc size; this was supported by experimental observation. Takeuchi et al. (1981) found that equilibrium flocculation for hardwood pulp decreased as the velocity increased, but showed no change for softwood pulp. Although deflocculation is a key issue, research focus has not been directed toward the understanding of the deflocculation mechanism until recent years. Kerekes et al. (1981) carried out visual studies of the dispersion mechanism of fiber flocs by using a cavity capable of creating shear layers and stationary vortices as the turbulence generation device. They observed stretching and rupturing of the flocs and concluded that shear layers and zones of extensional flows appeared to be more effective than vortices in dispersing the flocs. In his study of floc behavior in entry flow to constrictions, Kerekes (1983) observed that floc rupture was caused by tensile stretching rather than by shear. A more complete literature survey can be found in Lee (1982).

Experimental Apparatus and Procedure

The flow channel consists of two endless moving belts that form the movable walls of the channel. The belts are made of 0.254 mm (10 mil) clear Mylar film 0.2 m (8 in.) wide (z direction) with sprocket holes on either side. Each belt is supported

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by four rollers. The two end rollers provide tension lengthwise (x direction) while the two center rollers support the belt so that belt flapping does not occur. This arrangement can be set to convergent, divergent, and/or parallel flow configurations. The rollers can be moved in pairs in the x direction to vary the length of the different sections and can be independently moved in the y direction to vary the channel width. One of the end rollers for each belt is driven by a DC servo-controlled motor. The two belts are independently driven so that the belts can move in either the same or opposite directions.

Three 600 W and one 1,000 W projection lamps with polished aluminum reflectors were mounted below the tank. An adjustable slit was placed under the tank so that only the flow channel between the two movable walls was illuminated. This lighting system provides sufficient exposure of the flocs at f/2 and 1/2,000 s when the lights were placed 0.4 m from the center of the channel and at a right angle to the variable-speed movie camera (400 fps to 8,000 fps.). The zero mean velocity of the flow field provided a stationary view of the dispersion process. The entire sequence could be observed without moving the camera. This advantage allowed one to follow the dispersion history rather than observing only instantaneous occurrences. This is particularly important for a time-dependent process.

The pulp flocs used for this study were produced according to a technique developed by Jacquelin (1972), who artificially produced regular spheroidal flocs with well-defined boundaries by rolling a suspension contained in a drum. A long flexible softwood pulp was used because of its high tendency to flocculate. A 0.5% suspension was prepared by diluting a 36.6% pulp to make 1 L of suspension. A 2 L bottle was partially filled with the suspension and was rolled at a peripheral velocity of 15 cm/s for 2 h. A suspension of loose fibers and spheroidal aggregates, or flocs, was thus obtained. These spheroidal flocs with diameters of about 5 mm had a fairly uniform distribution. This suspension was then poured into a pan and diluted with 500 mL of water to aid separation of the flocs and the single fibers. The selection of flocs for the dispersion study was based on size and coherence. Coherence was determined by visual inspection, as the tighter flocs have higher reflectance. Flocs of about 5 mm dia. were sucked into a syringe that had been partially filled with water. The structure of the floc was thus undisturbed.

For each run about three flocs were introduced into the channel. The tip of the syringe was placed 1.5 cm into the channel; upon injection, the momentum of the flocs carried them to the center. Three flocs were used instead of one so as to increase the chance of recording a complete sequence of the dispersion, as some flocs would move out of view before they were dispersed.

The conditions selected for filming were parallel walls, with both walls moving in opposite directions at four different stress levels. A channel length to width ratio of 60 was used. Two different channel widths, 1 and 2 cm, each with four different belt speeds from 0.5 to 2.3 m/s, were used to create the simple Couette flow. A stationary side view was chosen for the high-speed filming.

Full details and drawings of the system are given by Lee (1982), as well as typical photomicrographs of the flocs used.

Results

Floc formation

The formation of pulp flocs in this study was achieved in a laminar environment where the fibers were at their sedimentation concentration with supernatant water. The peripheral velocity of 15 cm/s used was not high enough to maintain a homogeneous suspension with a consistency of 0.5%. The fibers settled and formed a mat. The flocculation process actually took place at a sediment concentration of about 0.7% or higher. The secondary flow caused by the rolling motion separated the mat of fibers into large patches or lumps on the order of several centimeters in size. As time progressed further fragmentation or flocculation of the aggregates caused them to approach an equilibrium size. At this stage the aggregates were not highly entangled and the boundaries of the aggregates were not sharply defined. The shape of the aggregates was also irregular but somewhat elongated in the direction of rolling. These loose aggregates at their equilibrium size then underwent compaction as a result of their interaction. The compaction is a process in which the aggregates grind against one another. The surface fibers bend and adhere to the surface or detach from the aggregate. Thus, the surface of the aggregate is smoothed and the loose surface fibers are removed. At the same time, the grinding action compresses the aggregate, causing rearrangement of the internal fibers, and a spheroidal floc with a very strong network takes form. By increasing the rolling time, flocs of more uniform shape and a higher degree of compaction can be obtained. Surface smoothness also increases as time progresses.

The flocs produced are expected to be much stronger than those that would exist in a paper machine, as the flow field employed for their formation is quite favorable and the duration of the formation was quite long. The advantages of using these flocs for dispersion study are better reproducibility and uniformity of the flocs. Using single flocs rather than a full suspension eliminated confusion and allowed observation to focus on the dispersion process.

Floc dispersion

The turbulent flow field between two oppositely moving belts has an S-shaped velocity profile. The average velocity across the flow is zero and there is very little mean velocity or mean shear in the turbulent central core region. This region is characterized by a turbulent zone without a mean velocity or mean gradient in velocity. Of course, there are intense turbulent fluctuations and local gradients. The stress, however, is uniform everywhere and depends only on the separation distance between the belts and the Reynolds number of the flow. The constant value of the stress field is independent of the state of the flow (laminar or turbulent) and nature of the fluid (Newtonian or non-Newtonian). The actual stress levels were calculated from a drag coefficient correlation given by Leutheusser and Chu (1971), and ranged from 0.75 to 8.92 N/m^2. The equation is

$$(2/C_f)^{1/2} = 5.75 \log [N_{Re}(C_f/2)^{1/2}] + 7.15 \qquad (1)$$

The stress itself is defined in the normal manner as

$$\tau = (1/2)\rho C_f U^2 \qquad (2)$$

A floc after being injected into the flow channel is subjected to these mean stresses as caused by the flow field. Since the floc is unable to follow the motion of the surrounding fluid, there exists a relative velocity between the floc and the fluid. This relative velocity results in direct stresses on the floc.

Based on our qualitative observations, the dispersion of a pulp floc involves two major processes, a global-scale disruption and a local or small-scale surface erosion. The occurrence of the former is stochastic in nature while the latter involves a rate process, but both are a result of the stresses in the system. The global phenomena include deformation, stretching, breaking, and fragmentation of the floc, as illustrated in Figure 1. The surface erosion process is a local phenomenon that may occur over all the floc surface. Shedding is a phenomenon that lies between these two in scale, but is also stochastic in nature. In this process a large portion of the floc is unaffected while a small portion of it detaches due to partial entrainment in a high-speed turbulent region smaller than the floc scale but greater than the fiber scale. In general, this mechanism is the same as the global disruption, but on a smaller scale.

When one considers the global phenomena or the floc as a whole, the scales of the flow field that are of interest are those comparable to the size of the floc; these will be termed floc-scale turbulence. The smaller scale turbulence only causes local effects. Larger scale turbulence, i.e., larger than the scale of the floc, may entrain the floc and cause translational motion. While this is occurring there may be a smaller relative velocity between the floc and its surrounding fluid that could cause local effects.

This simplest picture of a global destruction is one that involves two eddies or a region of high shear acting in opposite directions on two parts of a floc. The resultant forces acting on the floc may be separated into a tensile component and a normal component with respect to the floc centroid. The tensile force may stretch the floc into a stringy structure or a doublet, or

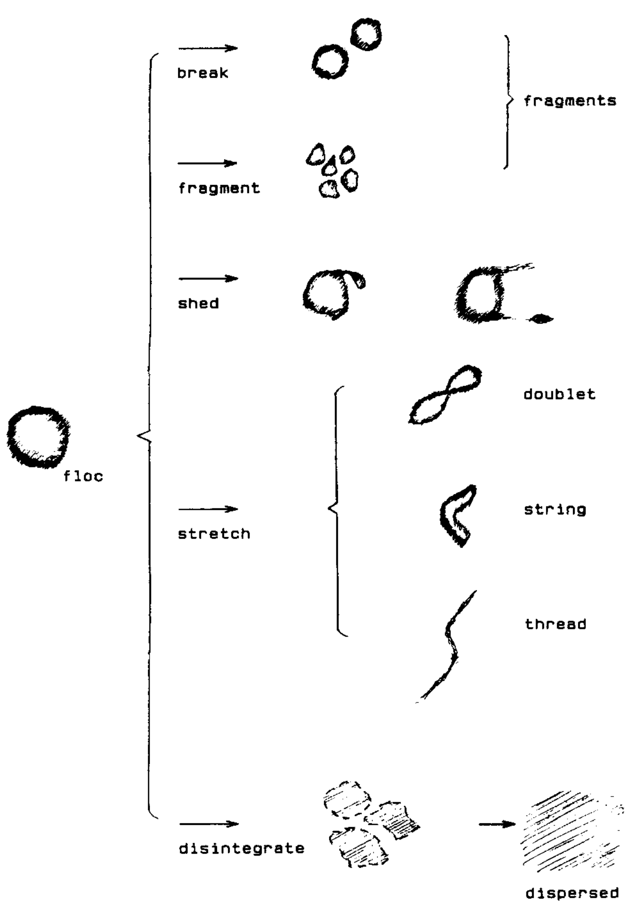

Figure 1. Observed dispersion phenomena.

break the floc depending on the stress level, the strength and structure of the floc, and the persistence of the disturbance. A stress field strong enough to overcome the strength of the floc, at least at a local level, is a prerequisite for floc dispersion. In a flow field where the floc-scale stress does not result in stresses on the floc that are high enough to break the floc, it may at most cause local-scale shedding and surface erosion.

At lower stress levels (<0.75 N/m^2), the global-scale phenomena are mainly due to the mean velocity gradient rather than turbulence in the core region. Depending on the Reynolds number and how close the floc moves to the wall, the floc may stretch and break or shed. At low Reynolds numbers, the velocity gradient is less steep and the strain rate is small; therefore breaking does not always occur. Long-lasting doublets and attached fragments are representative of this category. Doublets remaining in coherent rotational motion indicated the existence of slow, large-scale turbulence in the core region that entrains the entire floc. The floc follows the motion of the slow eddy with little relative velocity and hence the erosion rate is also small, if erosion occurs at all. As the stress level of the flow field increases progressively, the frequency of occurrence of breaking and fragmentation increases.

At a somewhat higher stress level (of the order of 2.6 N/m^2), the major cause of global-scale phenomena was the mean velocity gradient. But the higher velocity gradient resulted in higher frequency of breakage. In the core region some turbulent eddies also resulted in stresses greater than the yield stress of the floc and caused breakage, but the frequency of breakage was still low. At this turbulence level, the fragments no longer follow the fluctuating velocity closely and the local velocity differential caused the surface fiber to be washed away and the fragment eroded.

At even higher turbulence levels ($\geqq 5.3$ N/m^2) the turbulence in the core region results in high enough stresses on the floc to cause breakage. This also results in more frequent fragmentation during injection of the floc into the flow system. The fragments also stretch, break, and fragment further when they are in the core region. It was observed that breakage fragments sometimes moved in directions opposite the local mean flow direction, which indicates that turbulent eddies are the cause of the breakage. Erosion of surface fiber progresses at a higher rate due to the higher strain rate and thus results in a reduced total dispersion time.

High stresses are required to cause a global-scale destruction since more fibers are involved in this process. The mode of global-scale destruction, whether stretching or forming a doublet and then breaking, depends on the structure of the aggregate. In a less homogeneous aggregate, the fracture plane is likely to be one that has fewer fiber crossings. The fracture is not that of the fiber, but rather the detaching of these fibers from the parent aggregate. It also is not instantaneous. The strain has to exceed a certain limit before the two fragments are completely separated. Therefore, both strain rate and persistence of disturbance have to be considered. A homogeneous floc behaves like a viscoelastic material, as reported by Wahren (1964), who also measured the stress-strain relationship for fiber networks. When subjected to stresses that result in a net tensile force, the floc is elongated and the fibers are aligned in the direction of the tensile force. The resulting thread can be as long as several fiber lengths, which could be due to the staggering of the aligned fibers or the coherence of the turbulent structure that caused the stretching. Breaking of the thread does not always occur, immediately, as it depends on the duration of the applied tensile force and/or the coherence of the surrounding turbulent field. When the external force ceases, the stringy structure remains at its final strained state. Recoil, as would occur with an elastic material, has not been observed. Further coiling of the thread occurs as a result of the coherence of the surrounding turbulent flow field. Stretching occurs less frequently for the large flocs because homogeneity exists only at a smaller scale. For this reason, stretching of the entire floc immediately after injection is rare except for the cases where the floc structure is quite loose. These loose flocs are merely fragments of the initial sedimented fiber network that underwent the flocculation process to a lesser extent.

The global-scale disruption is a rapid size reduction mechanism compared to local surface erosion. It not only rapidly reduces the size of the floc but also increases the exposed surface area for further erosion. Moreover, the fibers that are pulled when the floc breaks may lead to weakening of the entire structure. However, the global-scale disruption does not lead to the final dispersion at the fiber level. To achieve such final dispersion, it has to be a local phenomenon. This process is the surface erosion in which the surface fibers are washed away by the surrounding fluid. As pulp fiber is flexible and cannot support a bending stress, this phenomenon must occur mainly due to forces resulting from skin drag in a direction tangent to the surface in the neighborhood of the fiber. This helps explain why erosion is usually associated with the rotation of a fragment. Rotation itself is a global phenomenon due to a net couple on the aggregate that comes from floc-scale disturbances. Any local relative velocity between the floc and the surrounding fluid that results in a drag force strong enough to pull the fiber away, causes local erosion of the floc surface. Mason (1977) in his study of *laminar* dispersion of particle aggregates indicated that closed streamlines caused the reattaching of particles as they moved into the closed streamlines region. In a turbulent field, the existence of local disturbances increases the probability of a detached fiber moving away from the floc.

The rate of size reduction of the floc due to erosion is expected to be related to the size of the floc. Size not only determines the total exposed surface area available for erosion, but also has an effect on the relative velocity. As the aggregate becomes smaller it becomes more stable because it is able to follow more closely the motions of the surrounding fluid. Hence, the velocity differential is reduced and the rate of erosion reduces as the aggregate becomes smaller.

The global disruption and surface erosion of the floc can reduce its size to a point where distinction between the mechanisms no longer exists. At this point any deformation involves the fragment as a whole. The effective floc-scale turbulence at this stage is small-scale turbulence. The dispersion of this final aggregate appears as an expansion into individual fibers. The existence of fine-scale turbulence is essential to achieve this final dispersion.

Time and rate of dispersion

The average total time required to disperse the pulp flocs at various stress levels is plotted in Figure 2. The differences due to the width of flow channel are statistically insignificant at a 5% confidence limit except for the lowest stress level, where no complete dispersion was observed for the narrow channel. Previously it was mentioned that at a low stress level, floc disruption is mainly caused by the mean velocity gradient. The mean velocity gradient near the wall in the narrower channel is smaller than that of the wider channel at the same stress level because of its lower Reynolds number. This might have resulted in the ineffectiveness of the narrow channel at the lowest stress level.

At higher stress levels, there was an effect of injection breakage. Injection breakage is equivalent to introducing smaller flocs into the stress field. Hence, it is expected they will require less time to disperse. Whether the early breakage enhances the subsequent dispersion rate is not known since the study is based on a fixed initial floc size. Observations of the flocs that remained quiescent before breakage suggest that the onset of destruction warrants further investigation. The high shear due to injection

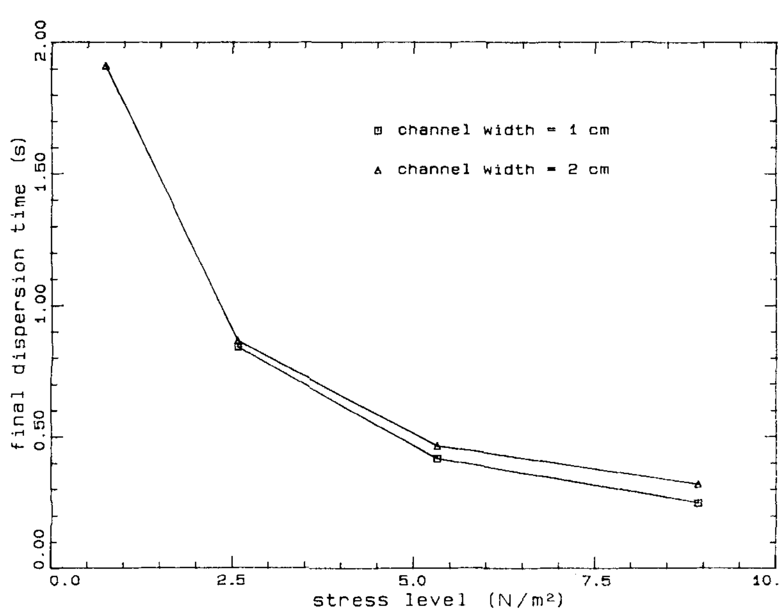

Figure 2. Total dispersion time as a function of stress level.

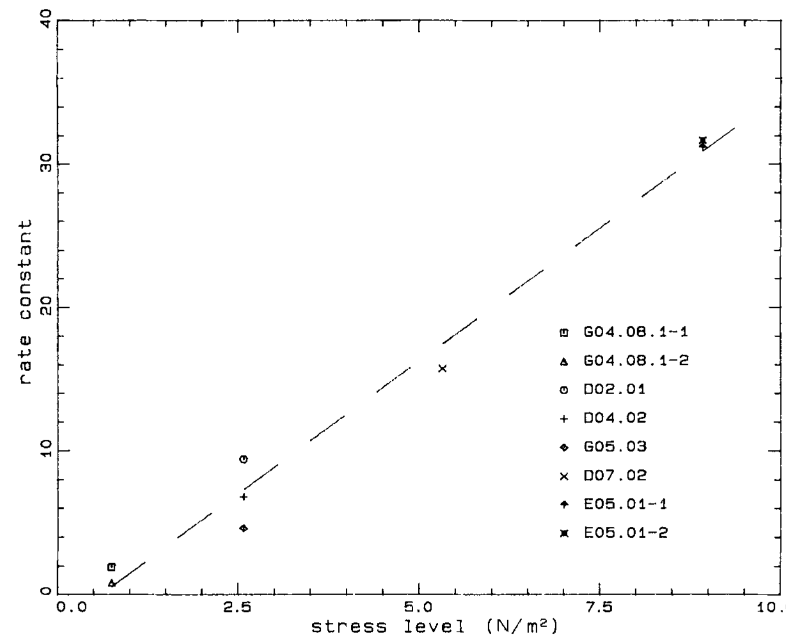

Figure 3. Floc dispersion rate constant.

breaks the floc much faster than does the flow field, which resulted in a significant difference in dispersion time.

Even though breaking is a fast process for size reduction, it still requires considerable time when the stress level is low. High stress and rapid breaking at the beginning is very favorable for dispersing the floc and shortens the final dispersion time to that normally attainable at higher stress levels. Early breakage that resulted in significantly shorter dispersion times showed that the dispersion time is comparable to that at the next higher stress level.

Information on the final dispersion time enables one to interpolate the results for the same initial size in the same flow field for the same type of floc. It does not tell anything about the history of the dispersion process. Rate information is essential before a model can be developed to predict the results. For this reason attempts were made to study the possibility of extracting rate information from the film records.

For several samples, their histories of projected size variation were obtained by tracing the contour of the floc from the projection screen at given time intervals. The area of the projected image was measured to serve as a measure of the size of the floc. This method was crude, but the results were encouraging. If one ignores the abrupt size changes, which are due to the irregular shape of the flocs, the size histories suggest that the size reduction due to erosion may be described by an exponential decay. Rate constants at various stress levels were then determined for

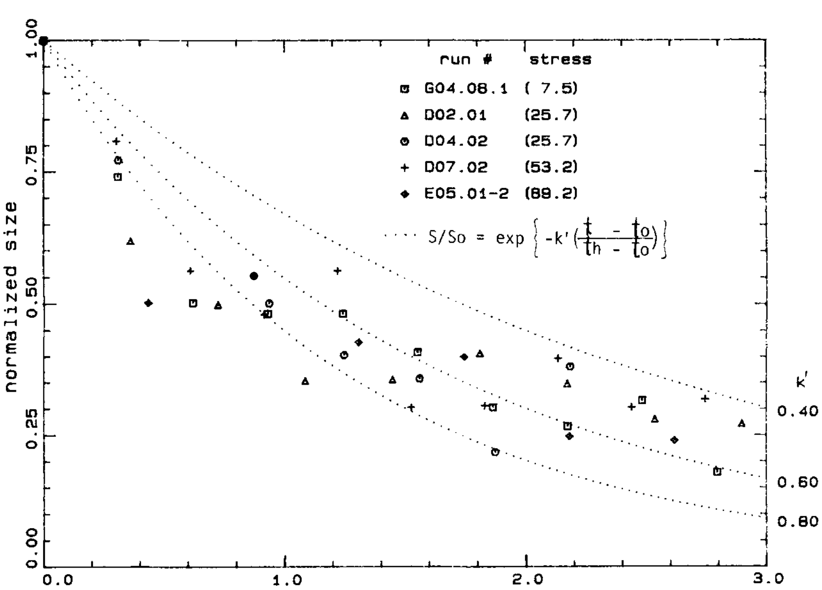

Figure 4. Normalized floc size history.

six samples. Figure 3 shows the variation of rate constant at different stress levels. This figure indicates that the rate constant may be represented by a linear function of the stress level. The intercept at a zero rate constant is a measure of the surface yield stress below which no erosion takes place. The rate constant from Figure 3 may be expressed as

$$k = 3.7(\tau - 6) \quad s^{-1} \tag{3}$$

for a normalized rate equation of the form

$$S/S_0 = \exp\left[-k(t - t_0)\right] \tag{4}$$

where S is the size and t is time, and subscript 0 refers to the starting conditions. This is a very crude model and the values obtained serve at most to show their approximate magnitudes. The result is encouraging, as it does show the possibility of collapsing data in this manner. If for each sample its half-life is taken as the normalizing factor, the time histories of these samples at different stress levels fall within a fairly narrow range, as shown in Figure 4.

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Notation

C_f = drag coefficient
h = half-channel width
k, k' = constants
N_{Re} = Reynolds number, Uh/ν
S = size
S_0 = initial size
t = time
t_h = final time for normalization
t_0 = initial time
U = belt velocity
ρ = density
ν = kinematic viscosity
τ = shear stress

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