Sedimentation Method to Evaluate PFI Mill Beating Degree of Wood Pulp Fibers

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Abstract: A sedimentation experiment was used as a simple method to evaluate the PFI mill beating degree of wood pulp fibers. The sedimentation volume decayed exponentially with elapsed time. The sedimentation rate, $k$, changed with the beating degree, though the equilibrium sedimentation volume remained relatively constant. The rate $k$ decreased with the increasing concentration, $c$, and the beating degree; and moreover, $k^{-1}$ was proportional to $c$. This result suggests that $k^{-1}c^{-1}$ can be a unique factor for the beating degree. The factor expresses the beating degree well and can also tell us that the single fiber properties are more important than inter-fiber interactions during the sedimentation process of the CSF measurement.

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1. Introduction

Mechanical treatment of wood pulp fiber in water is a necessary process in papermaking, and is well-known as beating or refining. The purpose of the beating is to change the wood pulp fiber properties to those desired for paper machine runnability and product properties. In the laboratory, the PFI mill is one of the most widely used refiners. During beating, fibers randomly and repeatedly undergo tensile, compressive, shear and bending forces [1]. There have been numerous studies that investigated the influence of the PFI mill beating on pulps, which is still the subject of many studies [2-6]. The PFI mill is a very useful tool to change the pulp and handsheet properties, and moreover to predict pulp strength properties [3]. However, it has long been recognized that the beating and refining action in the PFI mill differs from that of practical units. In 1990, a method was developed to characterize the pulp refiners using the C-factor, which represents the capacity of a refiner to impose impacts on pulp fibers [5]. The C-factor first made it possible to quantify the beating degree of the pulp fibers beaten in different refiners [6].

Freeness is also used to evaluate the beating degree of pulps due to its simplicity and usefulness. The freeness such as CSF (Canadian Standard Freeness) intrinsically consists of drainage and sedimentation processes. However, the physical meaning of the CSF value is still unclear. On the other hand, the sedimentation experiments have also been used to evaluate the chemical and physical changes in fibers [7,8]. The sedimentation volume can be easily determined and it also distinguishes the pulp fiber suspensions from different chip types and chip sections [9]. Recent research [10] shows that the sedimentation volume of the recycled pulp fibers is increased by the ultrasonic treatment, which implies that the flexibility and bulk of the fibers have been increased. Andersson [11] discussed the sedimentation processes in detail. He investigated the sedimentation volumes of various fibers and concluded that the flocculating tendency was related to the various properties of the fibers. However, the effect of time-dependent changes, such as initial sedimentation rate on the fiber properties, was hardly discussed.

In this study, a simple method was designed that can be used to evaluate the PFI mill beating degree of wood pulp fibers by measuring the sedimentation volume. We discussed the effect of the single fiber properties on the sedimentation process using variation in the sedimentation rate. The physical meaning of the sedimentation rate and its relation to the CSF value is also discussed.

2. Experimental

2.1 Material and the PFI mill beating

A commercially available softwood bleached kraft pulp was used in this study. The average length and diameter of the pulp fibers were 3.2 mm and 30 µm,
respectively. A 10wt% pulp fiber suspension was beaten with the PFI mill, according to TAPPI test methods T248. The revolution numbers were 5,000 and 20,000. The clearance and the load were 0.2 mm and 3.33 N/mm, respectively. The water retention values [12] of the fibers were 76.8% (unbeaten), 125% (lightly beaten), and 246% (heavily beaten). The unbeaten and beaten fibers were dispersed in distilled water to obtain pulp fiber suspensions of various concentrations.

2.2 Sedimentation measurement

The sedimentation volume, which is the volume of the fiber layer, was determined for the suspending fibers of various concentrations in a 200-ml measuring cylinder. After pouring 200 ml of the suspension into the cylinder, it was shaken to make the fiber suspensions thoroughly disperse, and it was then left for sedimentation. The sedimentation processes were observed versus corresponding time [10]. The sedimentation volume change was expressed by $V_s$, which is defined by the sedimentation volume / total volume.

![Fig. 1 Typical appearances of the fibers produced at different beating degrees. The revolution numbers are (a) 0, (b) 5000, and (c) 20000. Bar: 400 μm.](image)

![Fig. 2 Sedimentation volume change, $V_s$, versus elapsed time, $t$, for unbeaten fiber suspension at various concentrations.](image)

![Fig. 3 Sedimentation volume change, $V_s$, versus elapsed time, $t$, for lightly beaten fiber suspension at various concentrations.](image)
3. Results and discussion

Fig. 1 shows typical appearances of the fibers produced at different beating degrees. The changes in their geometric shapes are not obvious. However, with an increasing beating degree, the development of external fibrils on the surface of the fibers became noticeable.

Figs. 2, 3, and 4 show the sedimentation volume changes, \( V_s \), versus elapsed time, \( t \), for the unbeaten, lightly beaten (5,000 rev.), and heavily beaten (20,000 rev.) fiber suspensions at various concentrations, respectively. We consider that the sedimentation of the fiber suspensions includes two states: the initial sedimentation state and the equilibrium state. As shown in these figures, the \( V_s \) curves of any concentration rapidly decrease during the initial state. With time, each \( V_s \) curve shows a plateau of a constant volume, which means the system reaches an equilibrium state. By comparing these figures, we found that the time required for the system to reach an equilibrium state increases with the beating degree.

Fig. 5 shows the plots of \( V_s \) versus \( t \) for the fiber suspensions of different beating degrees. It is unlikely to directly evaluate the beating degrees from the \( V_s \) values because the \( V_s \) curves of different beating degrees show almost the same values of \( V_s \) at the same concentration. However, we found that the sedimentation rates of the fiber suspensions of different beating degrees were distinct for the initial sedimentation state as shown in Fig. 5. Here, the exponential equation can be fitted to evaluate this distinction, which is expressed by equation 1.

\[
V_s(t) - V_s(\infty) = (1 - V_s(\infty)) e^{-kt} \tag{1}
\]

where \( k \) is the sedimentation rate of the fiber suspension, which can be obtained from the slope of the plots of \( \ln(V_s(t) - V_s(\infty)) \) versus \( t \). \( V_s(\infty) \) is the sedimentation volume change at infinite time, which was measured from the plateau at 120 min. As described above, \( V_s(\infty) \) at the same concentration is independent of the beating degree. The sedimentation is thus considered as a delayed process in which the sedimentation structure arrives at the same equilibrium. The \( k \) value represents the rate that the sedimentation structure changes, and is a function of the beating degree.

Figs. 6, 7, and 8 show the natural logarithmic plots of \( V_s \) versus \( t \) for the unbeaten, the lightly beaten, and the heavily beaten pulp fiber suspensions, respectively. The figures show that the value of \( \ln(V_s(t) - V_s(\infty)) \) exponentially decreases at the initial state and the \( k \) value, which was obtained from each slope, decreases with the increasing fiber concentration. Here, we must explain that the fitting lines do not include the data points within 1 min. This is because within the first 1 minute the sedimentation structure had just begun to form, so that their upper surface was unclear and difficult to correctly read.

Fig. 9 shows the sedimentation rate, \( k \), versus concentration, \( c \), for the fiber suspensions of different beating degrees.
beating degrees. The rate $k$ shows a rapid decrease with the increasing concentration for all the fiber suspensions. This result corresponds with a previous study [10]. This fact suggests that $k$ is closely related to the concentration. Though the beating affect the fibers in various ways [1,2], the effects on the stiffness and the fibrillation of the fibers are considered to be the primary factors. By beating, the fibers become flexible and external fibrils are produced on the surfaces of the fibers as shown in Fig. 1, which means an increase in the specific surface area of the fibers. This induces higher water retention values of the fibers. The hydrodynamic volume of a single fiber then becomes greater than that of the unbeaten one. Therefore, the sedimentation rate during the initial state was delayed by beating, i.e., the $k$ value at the same concentration decreases with the increasing beating degree.

The inverse in $k$ represents the specific time in which the sedimentation structure changes. Fig. 10 shows the concentration dependence of $k^{-1}$ for the fiber

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**Fig. 6** Natural logarithmic plots of $V_s$ versus $t$ for unbeaten fiber suspension.

**Fig. 7** Natural logarithmic plots of $V_s$ versus $t$ for lightly beaten fiber suspension.

**Fig. 8** Natural logarithmic plots of $V_s$ versus $t$ for heavily beaten fiber suspension.

**Fig. 9** Sedimentation rate, $k$, versus concentration, $c$, for the fiber suspensions of different beating degrees.
suspensions with different beating degrees. The $k^1$ value strongly depends on the concentration. For the fiber suspensions with the same beating degree, the $k^1$ value linearly increases with the increasing fiber concentration. By extrapolating each line to zero concentration, the $k^1$ value also becomes zero. This fact also implies that the $k^1$ is directly proportional to the concentration. Moreover, the change in $k^1$ (i.e., the slope of each line) increases with the beating degree. This suggests that $k^1$ can be used as a criterion for the beating degree. In the sedimentation process, the fiber suspension changes from thoroughly dispersed state to an equilibrium state; this process can be considered as a kind of relaxation process. That is, $k^1$ is a kind of relaxation time.

Because $k^1$ is proportional to $c$ for the dilute fiber suspensions, the inter-fiber interaction has almost no effect on the sedimentation process. If the inter-fiber interaction becomes more remarkable, higher order terms of $c$ should appear analogous to the theory of chemical reaction rate. Therefore, $k^1$ reflects the changes in the intrinsic property of a single fiber rather than the inter-fiber interaction. From this hypothesis, we can derive equation 1 as shown in the appendix section.

The sedimentation factor defined by $\beta = k^1 c^{-1}$ should be a $c$-independent factor, which describes the effect of the beating degree on the fibers. The $\beta$ factor will be a function of the physical properties of a single fiber, such as geometric shape, axial ratio, specific surface area, elastic modulus, and so on. Fig. 11 shows $\beta$ as a function of the PFI mill revolutions. Fig. 11 also contains the CSF values as a reference. The $\beta$ factor shows a linear increase with the increasing PFI mill revolution numbers. It is concluded that $\beta$ is a useful factor to evaluate the beating degree of wood pulp fibers similar to CSF. As described above, the mechanism of the CSF is complicated and not known well. However, the sedimentation factor, $\beta$, evaluates the intrinsic properties of a single fiber in the sedimentation process. This can help us to understand the role of the single fiber during the sedimentation process of the CSF measurement.

4. Conclusions

A sedimentation method was developed to evaluate the PFI mill beating degree of wood pulp fibers. The sedimentation rate, $k$, decreases with the increasing fiber concentration and beating degree. It is found that $k^1$ is proportional to the concentration. The linear relation of the sedimentation factor, $\beta$, to the beating degree shows that the PFI mill is very efficient and supports the fact that the beating process is an energy intensive process by the refiners [1,5,6].

Compared to other methods used to evaluate the beating degree [1-4], the present method requires no special measurement device. Furthermore, $\beta$ is a useful factor to evaluate the intrinsic property of single fiber in a sedimentation process. The results show that the single fiber motion is a very important factor in the sedimentation process of the CSF measurement. This handy method can also be used to evaluate other fibrous particle materials.
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Appendix

Here we derive equation 1 from the hypothesis that the sedimentation process can be described with a single fiber motion. In the sedimentation process, the fibers sedimentate with uniform velocity, \( u \), feeling fluid resistance. From the balance of gravity and the resistance, the velocity of the settling fiber is expressed by

\[
u = \frac{mg}{6\pi a \eta}
\]

where \( m \), \( a \), and \( g \) are the mean fiber mass, the hydrodynamic radius of the moving fiber, and the gravitational acceleration. \( \eta \) is the viscosity of the dispersion medium, which can be replaced by the suspension viscosity when the system is dilute [13-15].

In the dilute suspension, the suspension viscosity is proportional to the concentration of the fibers, \( c \). Therefore, \( u \) is in inverse proportion to \( c \). This is strongly supported by Fig. 9, in which the sedimentation rate varies inversely as \( c \). The concentration \( c \) increases during the sedimentation. That is, \( c \) is a time-dependent factor and in inverse proportion to the sedimentation volume, \( \Delta V \); and moreover \( v \) is proportional to the height of the settling fiber column, \( h \). This is expressed by

\[
\eta \propto c \propto v^{-1} \propto h^{-1}.
\]

Using expression 2 and 3, it is found that \( u \) is proportional to \( h \). The height \( h \) is a function of time, \( t \), i.e., \( h = h(t) \). Let the height of the fiber column after a very small interval of time \( \Delta t \) be \( h(t+\Delta t) \). The fibers settle through the distance \( u(t)\Delta t \) in the interval of time \( \Delta t \), and so does the whole fiber column as expressed by equation 4:

\[
h(t+\Delta t) - h(t) = -u(t)\Delta t.
\]

As \( u(t) \) is proportional to \( h(t) \), we can replace \( u(t) \) in equation 4 with \( kh(t) \), where \( k \) is a constant including the \( a \) factor. We then replace equation 4 with a form of differential equation:

\[
\frac{dh(t)}{dt} = -kh(t).
\]

We can solve equation 5 using the boundary condition, and then equation 6 is derived:

\[
h(t) = h(0)e^{-kt}.
\]

We can obtain equation 1 by replacing \( h(t) \) with \( (v(t) - v(\infty))/v(0) \) and by using the relation of \( v(t)/v(0) = V_s(t) \) as is written in Section 2.2:

\[
V_s(t) - V_s(\infty) = (1 - V_s(\infty))e^{-kt}.
\]

This derivation supports our suggestion that the single fiber properties are important in the sedimentation process. Furthermore, the \( k \) factor varies inversely as the factor \( a \), which is an index of the single fiber properties.

References