Pressure loss and velocity profile of pulp flow in a circular pipe

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ABSTRACT *Fiber suspension flow in a circular pipe was studied by measuring the pressure loss between two axial positions and local velocity. The pressure loss was measured by pressure transducers, and local velocity was measured by using an electrochemical technique. From the relation between the friction factor and the Reynolds number, which was determined for each fiber suspension viscosity, there appeared to be three flow regions: laminar, transitional, and turbulent. Additionally, in the turbulent region, the velocity profile in the range of lower Reynolds number was different from that in the range of higher Reynolds number. An index for turbulent intensity is introduced.*

KEYWORDS
Fluid dynamics
Hydrodynamic pressure
Laminar flow
Pulps
Reynolds number
Transition flow
Turbulent flow
Viscosity

The flow mechanics of fiber suspensions has been studied for more than 25 years, but the flow behavior of the suspension is complicated and has not been made clear. For elucidating the flow mechanics, it is indispensable to study the flow in a circular pipe, which plays an important part in papermaking processes. There have been many studies on the pulp flow in a circular pipe, but some problems are left to be solved. One of them lies in the relation between pressure loss and flow rate.

This relation has been said to be different from that of water (*1, 2*), but the discussion has been based on a curve of pressure loss vs. flow rate. Even if a curve of pressure loss vs. Reynolds number is used, the characteristic viscosity in the Reynolds number is that of water as the mother liquor. To develop the concept with accuracy, we have to introduce the Reynolds number based solely on the viscosity of the pulp, which has not been defined clearly.

Another important problem has to do with the velocity profile under turbulent flow. Based on measurements of local time-averaged velocities made by using an impact probe, the turbulent velocity profile is said to become a logarithmic distribution (*1-4*). But the impact probe is not always suitable for measuring the velocity of the fiber suspension flow, especially when the size of the probe is not small enough compared with the inner diameter of pipe, which is usually the case. Then the velocity profile obtained has no accuracy. Therefore, it is desirable to measure it by making use of a new technique.

Our purpose was to obtain the experimental relation between the friction factor and the newly proposed Reynolds number for the pulp flow in a circular pipe based on the data of pressure loss. Here, we discuss the turbulent velocity profile based on the data of local time-averaged velocity taken by using an electrochemical technique.

Results and discussion

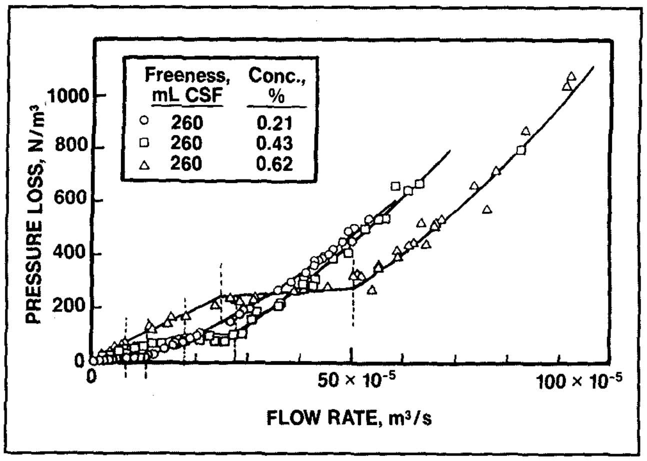
Flow characteristics of fiber suspensions

Some examples of the experimental relations between the pressure loss and the flow rate are shown in **Figs. 1 and 2**. Figure 1 shows the relations for various values of the pulp fiber concentration, and Fig. 2 shows those for various values of freeness. These figures show that the relation does not depend on values of freeness, at least in the experimental region, but that they do depend on pulp fiber concentration.

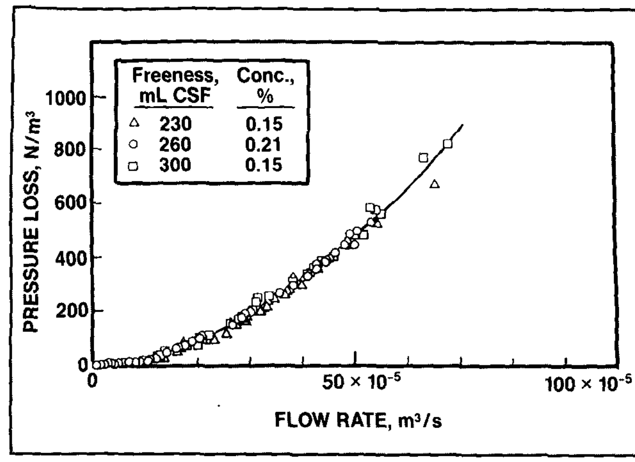
In every experimental condition, the shape of the curve on the pressure loss chart can be divided into three regions, as shown by the broken lines in Fig. 1. These regions are characterized by:

- Lower flow rate, in which the pressure loss increases gradually
- Intermediate flow rate, in which the pressure loss takes almost constant value

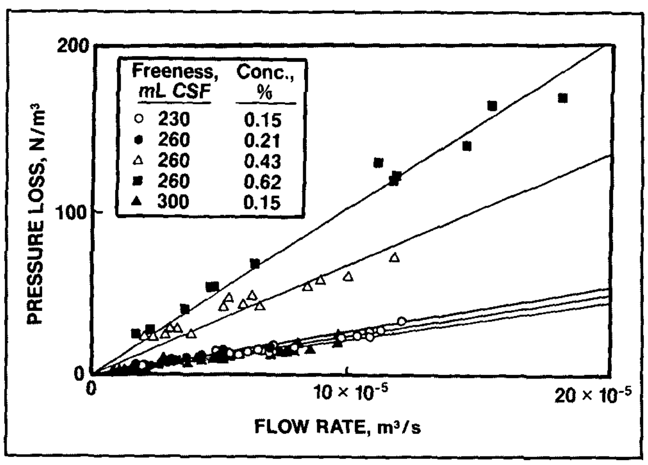
1. Pressure loss vs. flow rate for various values of pulp fiber concentration



2. Pressure loss vs. flow rate for various values of freeness



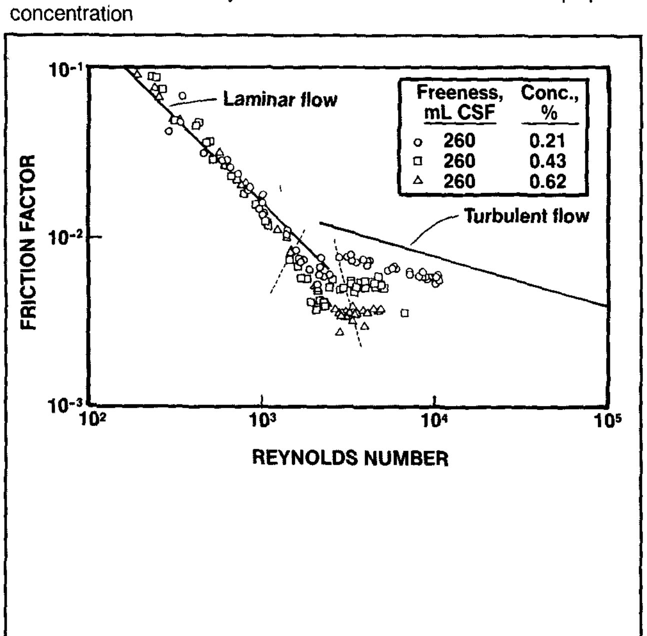
3. Pressure loss vs. flow rate in the lower flow rate region



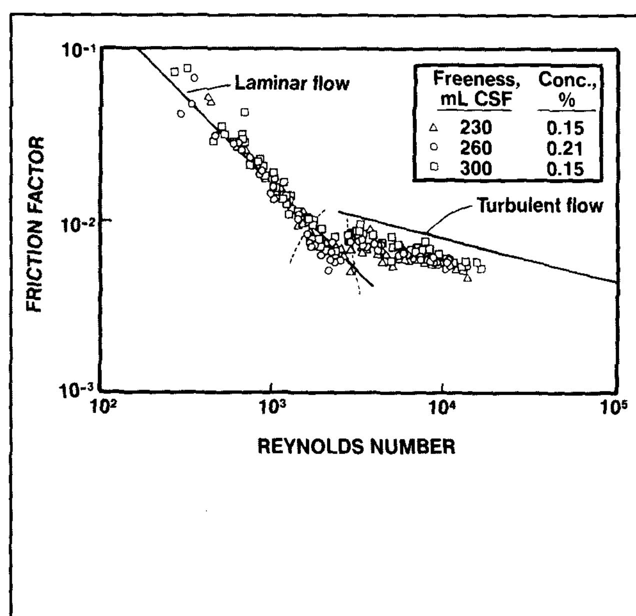
I. Apparent viscosity, μ, for various values of pulp fiber concentration and freeness

Freeness, mL CSF	*Conc., %*	*Viscosity, $\mu \times 10^3$, kg/(m·s)*
230	0.15	2.40
260	0.21	2.51
260	0.43	6.36
260	0.62	9.70
300	0.15	2.11

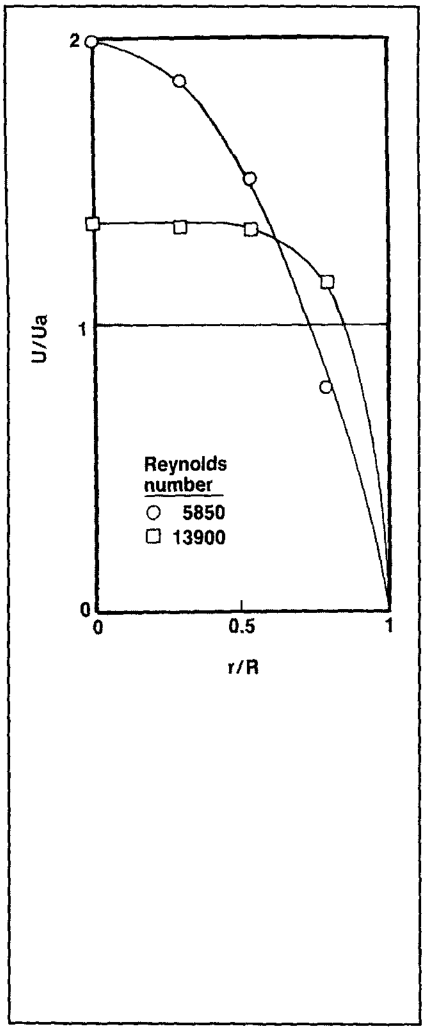
4. Friction factor vs. Reynolds number for various values of pulp fiber concentration



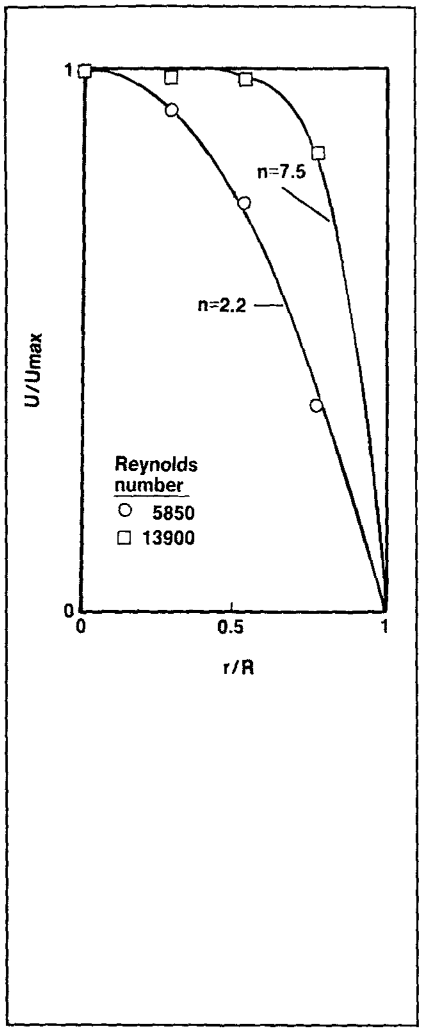
5. Friction factor vs. Reynolds number for various values of freeness



6. Velocity profiles in the turbulent flow region. Freeness = 260 mL. Conc. = 0.21%.



7. Velocity profiles approximated with Eq. 4. Freeness = 260 mL. Conc. = 0.21%.



- Higher flow rate, in which the pressure loss increases steeply.

These three regions reflect the plug, the mixed, and the turbulent flows, respectively, which are known from previous research (*2*). Additionally, these three regions bear a close analogy with the three regions in the case of circular pipe flow of water—i.e., the laminar, the transitional, and the turbulent flow.

As shown in **Fig. 3**, when the relation in the region of lower flow is magnified, the pressure loss seems to be proportional to the flow rate for each fiber suspension. This tendency is just peculiar to laminar flow in Newtonian fluid. So the fiber suspension in the lower flow rate region can be treated as a Newtonian fluid, and the apparent viscosity of each fiber suspension can be calculated from the slope of each straight line, based on Hagen-Poiseuille's law. The calculated values of the particular apparent viscosity for various values of weight concentration and freeness are shown in **Table I.** The value of the particular apparent viscosity increases as the pulp fiber concentration increases. By using this particular apparent viscosity, the Reynolds number can be defined as

$$Re = 2\rho\, u_a R/\mu \qquad (1)$$

where

ρ = the density of fiber suspension, kg/m^3

u_a = the cross-averaged velocity, m/s

R = the inner radius, m

μ = apparent viscosity, kg/(m·s).

Plotting the friction factor vs. the Reynolds number is much simpler than plotting the pressure loss vs. the flow rate. **Figures 4 and 5** show the experimental relations between the friction factor and the Reynolds number as defined in Eq. 1 for circular pipe flow of each fiber suspension. Again, the relation does not depend on freeness but on the pulp fiber concentration.

This result indicates that the difference of the value of freeness within the range of 230-300 mL CSF is not important for the flow mechanism of fiber suspension under these experimental conditions. Of course, the flow mechanism is affected by the types of pulp fiber and the large difference in the freeness value. The solid lines in these figures indicate the relation for water:

For laminar flow, with $Re < 2.1 \times 10^3$

$$f = 16/Re \qquad (2)$$

For turbulent flow, with $2.1 \times 10^3 < Re < 10^5$

$$f = 0.0791/Re^{1/4} \qquad (3)$$

where

f = friction factor.

Equation 3 is the Blasius's formula. The broken lines in these figures show the boundaries of the laminar, the transitional, and the turbulent flows, which are based on the results in Figs. 1 and 2. Experimental data in the laminar flow region can establish the laminar line, which is written by Eq. 2 for the Newtonian fluids. The ranges of Reynolds number of 1500-2500 and of more than 2500 can be thought to correspond to the transition and the turbulent flow regions, respectively. The critical Reynolds number for the laminar-turbulent transition is almost the same as that of water.

Considering these results, the Reynolds number defined by Eq. 1 seems to be a criterion for determining the state of the pulp flow in a circular pipe. In the turbulent flow region, the friction factor takes a smaller value with an increase in the fiber concentration.

Velocity profiles of turbulent flow

Figure 6 shows two examples of the measured velocity profiles in the turbulent flow region, which are normalized by the cross-averaged velocity.

The velocity profile at Re = 5800 resembles closely a parabolic profile. However, that at Re = 13,900 looks like a plug profile, which is flat in the vicinity of the center of circular pipe. From these results, the following flow mechanics can be considered. The velocity profile in the turbulent flow region is not unique; in the turbulent range of lower Re, the profile is extremely different from that in the turbulent range of higher Re. Previous research has shown that the fiber network region that composes a plug disappears gradually according to the change of flow state in the order of laminar flow, transitional flow, and turbulent flow (*2*). So only a very thin fiber network region remains at the pipe axis in the turbulent range of lower Re, and the velocity profile becomes similar to the parabolic one. On the other hand, the inertia force is superior to the viscous force in the turbulent range of higher Re, and the velocity profile becomes flat in the vicinity of the center of the circular pipe.

We tried to express these velocity profiles by using the following simple equation:

$$u/u_{max} = 1 - (r/R)^n \tag{4}$$

where

u_{max} = the local velocity at a pipe center

r = radius, m

n = exponent that represents a velocity profile.

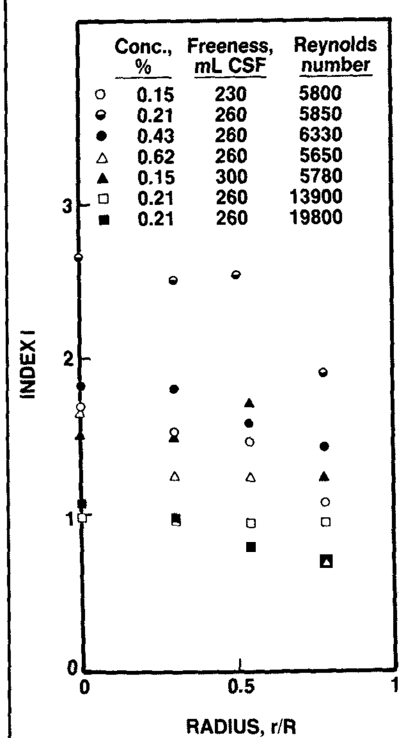
This equation contains one adjustable parameter, n. Results show that the velocity profiles in the turbulent flow region can be expressed approximately by this equation. The results of the two examples in Fig. 6 are shown in **Fig. 7**. The values of n for each fiber suspension are given in **Table II**. As the table shows, the values of n for the range of lower Re are smaller than the values for the range of higher Re.

Turbulent intensity is one of the important statistical quantities that represent the characteristics of turbulent flow and has some effects on the deformation of pulp fibers. But the velocity measuring probe we used is not suitable for measuring just the turbulent intensity, though it can measure the time-averaged velocity

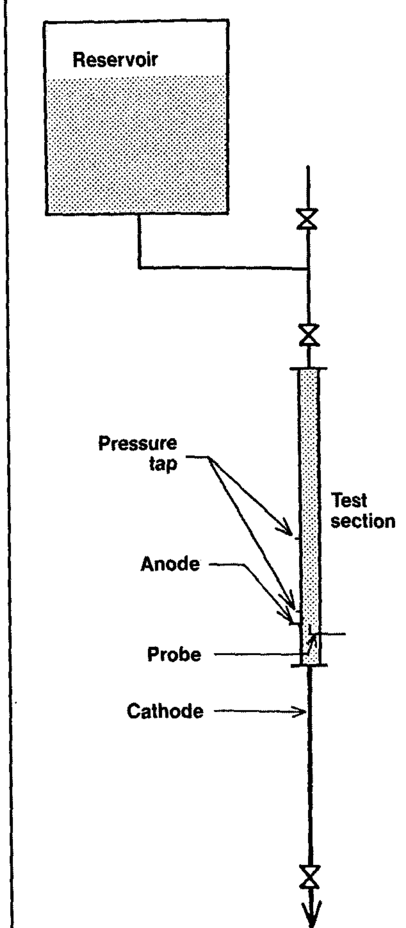
II. Values of *n*, exponent in Eq. 4

Freeness, mL CSF	*Conc., %*	*Reynolds number*	*Viscosity, n × 10³, kg/(m·s)*
230	0.15	5800	2.4
260	0.21	5850	3.1
260	0.43	6330	2.2
260	0.62	5650	2.4
300	0.15	5780	2.8
260	0.21	13900	7.5
260	0.21	19800	5.0

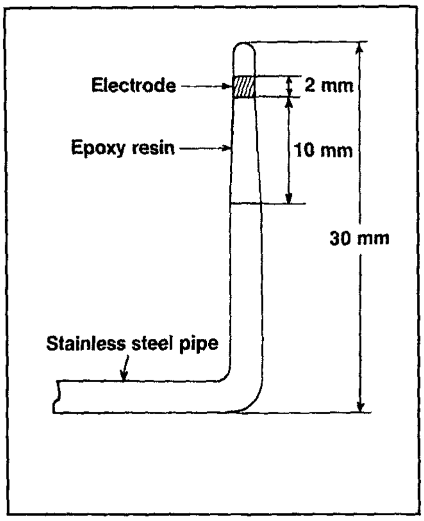
8. Radial distribution of the index for turbulent intensity, I, where *r/R* is the radius divided by the inner radius



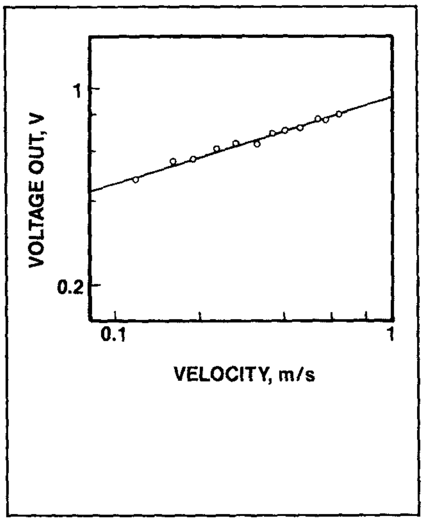
9. Experimental apparatus



10. Velocity measuring probe



11. Calibration line of velocity measuring probe



well enough. The output signal from the probe reflects not only the real velocity but also the effects of the behavior of the pulp fiber such as fibers being close or striking.

From these readings, the value of the difference between the maximum and minimum velocity is calculated. Though it is usual to normalize the turbulent intensity by local mean velocity, just the value of the difference is useful in comparing the effects of velocity fluctuation on the deformation of pulp fibers at various radial positions. Therefore, the values are normalized not by local mean velocity but by cross-averaged velocity.

Figure 8 shows the normalized value, I, at each radial position for each fiber suspension. The value of the index near the pipe wall is smaller than those values at the inner parts. In addition, the index takes a smaller value with an increase of the Reynolds number.

Experimental procedures

The test fiber suspension consists of beaten hardwood bleached kraft pulp, ion-exchanged water, and electrolytes for an electrode reaction controlled by mass transfer rate (3 mol/m^3 potassium ferrocyanide and potassium ferricyanide and 100 mol/m^3 potassium chloride) (*5-7*). Table I shows the weight concentration and freeness of the test fiber suspensions.

Figure 9 depicts the experimental apparatus. The test section made of acrylic resin (25 mm in inner diameter and 2 m in length) is set vertically. The flow rate is regulated by the valve connected to the end of the test section. Two pressure taps are set at 1350 mm and 1850 mm downstream of the entrance of the test section, respectively. The pressure loss is measured by pressure transducers.

The local velocity is measured by the electrode probe, illustrated in **Fig. 10.** Pulp fibers flow through along the blunt nose tip, and the belt-shaped electrode is scarcely covered with pulp fibers. The probe is set at 1900 mm downstream of the entrance of the test section, and the local velocity is measured at four radial points. The probe is calibrated by using a rotating annular open channel (*8*) filled with the same fiber suspension as that for the pipe flow. The velocity and the output voltage converted from diffusional electric current are correlated well by a straight line on a logarithmic graph paper, as shown in **Fig. 11.**

Conclusions

We studied the transitional and the turbulent flow of fiber suspensions by measuring the pressure loss and the local velocity.

The Reynolds number is newly defined by making use of the particular apparent viscosity of the fiber suspension. Three flow regions—the laminar, transitional, and turbulent regions—are defined from experimental relations between the friction factor and the Reynolds number. In the laminar flow region, the friction factor and the Reynolds number correlate well with the same equation as that in the case of Newtonian fluid, $f = 16/Re$. In the turbulent flow region, the friction factor takes a smaller value with an increase of the pulp fiber concentration.

The velocity profile is measured in the turbulent flow region. The velocity profile in the turbulent flow region is not unique. The velocity profile in the turbulent range of lower Re resembles closely a parabolic one. In the range of higher Re, it becomes flat in the vicinity of the center of the circular pipe. The velocity profiles measured can be expressed approximately by simple equations. In addition, we introduce an index concerning turbulent intensity.□

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