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# Flow Properties of Wood Pulp Suspensions in Pipes

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***Abstract*—**The flow of suspensions of wood pulp fibers in circular pipes has been investigated experimentally. The flow characteristics of pulp suspensions are discussed with regard to five flow regimes designated by the author. In particular, the effects of the shear stress at the pipe wall on the disruption and dispersion of networks of pulp fibers are examined. The values of the disruptive and dispersive shear stresses are formulated as simple expressions depending on only the fiber concentration. Furthermore, the flow properties of the suspensions are described using the yield shear stress.

***Keywords*—**Fiber Concentration, Flow Properties, Pulp Suspension, Yield Shear Stress.

## I. Introduction

UNDERSTANDING the flow characteristics when wood pulp suspensions are transported in conduits are very important in the process of manufacturing paper. Numerous reports [1]–[4] have been presented on the pressure loss in pipes. Furthermore, studies of pulp suspensions have recently been regarded as important for reducing energy consumption in the papermaking process[5]–[7].

A flow of pulp suspension is known as a solid-liquid two-phase flow and pulp suspensions have flocculation properties. Moreover, pulp suspensions flow as an aggregate of pulp fibers, which repeatedly flock and disperse. Thus, even when the pulp liquid has an extremely low concentration, the flow shows complex behavior different from that of water flow. That is, when the flow velocity $U_a$ is low, the pulp suspension exhibits similar behavior to a Bingham fluid. Such non-Newtonian properties of pulp suspensions become more pronounced with increasing concentration of the pulp fibers, and also the yield shear stress increases markedly. See Fig. 1 [8] for details. However, only a fragmentary qualitative explanation of fiber behavior has been given. Hence, we are currently far from explaining the relation between the pressure loss $\Delta P$ and flow rate in an actual pulp suspension flow [9].

In this study, we first measure the pressure loss of pulp suspensions with various fiber concentrations in circular pipes. Then, for each flow pattern that is classified according to previous findings [8], we investigate the effects of the fiber concentration, flow velocity and pipe diameter on the shear stress on the pipe wall. Moreover, we discuss our results from the viewpoint of rheology and also clarify the flow properties.

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## II. Experimental Apparatus and Procedure

### *A. Experimental Apparatus and Test Pulp Suspensions*

A schematic diagram of the experimental apparatus is shown in Fig. 2 [8]. The apparatus consists of a circulating pipeline, a test pipe, and visualization and measuring devices. The working fluid was a wood pulp suspension and was supplied to the test pipe from the reservoir by a magnetic pump. The flow rate of the fluid was adjusted by a flow control valve and was measured by an electromagnetic flow meter.

Five test pipes made of transparent acrylic and glass were employed. They had inside diameters $d$ (=2$a$) of 8, 10, 21, 22 and 40mm. The origin of the coordinate system used for analysis in this study is the pipe axis, and the $r$-axis is in the radial direction. The working pulp suspensions were Kraft pulp (LBKP: Laubholz bleached Kraft pulp). The raw material was mainly made from broadleaf trees.

The experiments were performed at fiber concentrations $C_s$ of 0.2 to 3%.

### *B. Measuring Method*

Experiments were conducted to measure the pressure loss. Moreover, the velocity distribution was measured and the flow visualization was made. The pressure loss between two taps was measured by a diffusive-type, differential pressure transducer made of a semiconductor and by a manometer.

The flow was visualized by a light-section method [10]. The flow in the horizontal plane including the pipe axis was photographed from the upper side with a high-speed camera (Photron, FASTCAM-1024 PCI). The fluid velocity in the axial direction was measured using an ultrasonic velocity profiler (UVP), by particle image velocimetry (PIV) and by laser Doppler velocimetry (LDV). Combining the data, we obtained the velocity distribution on the $r$-axis.

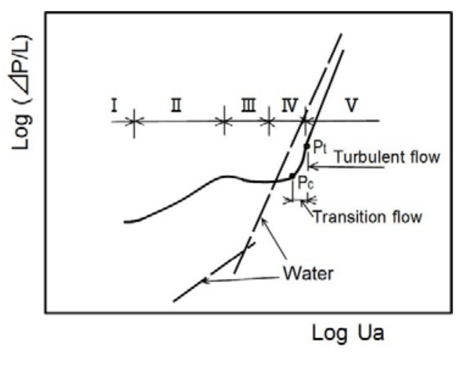


Fig. 1 Schematic diagram of relationship between pressure loss and velocity and flow regime

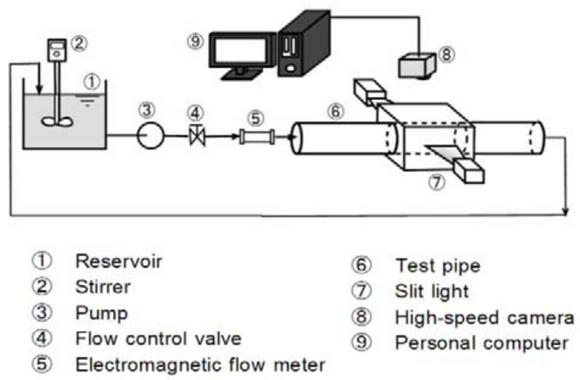


Fig. 2 Schematic diagram of experimental apparatus [8]

## III. Results and Discussion

In the author's previous report [8], he found that the flow of pulp suspensions in a square duct can be classified into five patterns from the viewpoint of the pulp fiber behavior, as shown schematically in Fig. 3.

In Fig. 4, we first show an example of results for the pressure loss at several fiber concentrations in a circular pipe. The relation between the pressure loss and mean fluid velocity appears to form a similar curve for different concentrations, although different pipe diameters and raw materials of the pulp were used in previous experiments [1]–[4]. Unfortunately, there are still many unknown points with regard to the problem that such flow behaviors appear under what conditions [9]. To survey these points, it is essential to appropriately define the strength of fiber networks and then to find the flow field at which the formed flocks disperse. For the disruption of flocks, it is necessary that the shear stress in a flow field is greater than the strength of the fiber networks. We can consider the yield shear stress as a useful index for evaluating the strength of fiber networks. In the following, with the above viewpoint, we will discuss the flow characteristics shown in the $\Delta P/L$—$U_a$ curve in Fig. 1.

The fibers flowing in pipes are not distributed uniformly as shown in Fig. 3. Therefore, the relation between the shear stress and the shear rate of a pulp suspension flow is different from that for a homogeneous Newtonian fluid. Fig. 5 shows the viscosity $\mu_w$ at the pipe wall versus the mean velocity $U_a$ in the pipe of $d$=22mm. The broken lines in Fig. 5 show where the flow pattern of $C_s$=0.8% divides. Approximating the experimentally obtained velocity distribution by $u=u(r)$, we calculate the viscosity $\mu_w$ as

$$\mu_w = \tau / \left(-du/dr\right)_{r=a} . \tag{1}$$

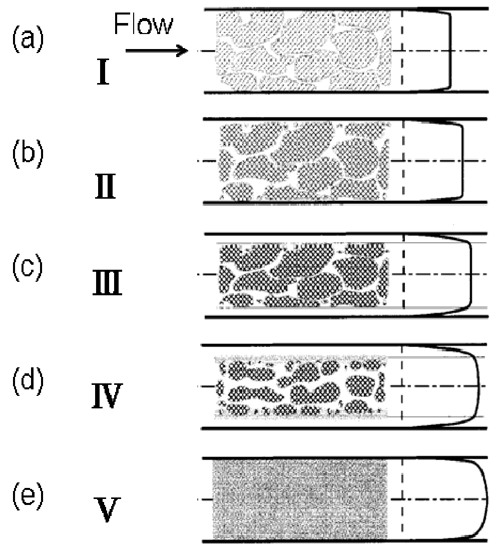


Fig. 3 Typical flow patterns of pulp suspensions [8] (a) Pattern I: Plug flow with strong interaction between fiber and pipe wall. (b) Pattern II: Plug flow with hydrodynamic shear and fiber-wall interaction. (c) Pattern III: Plug flow with water annulus in laminar shear. (d) Pattern IV: Mixed flow with fiber/water annulus and transitional flow from laminar to turbulent. (e) Pattern V: Turbulent flow with distributed pulp fibers

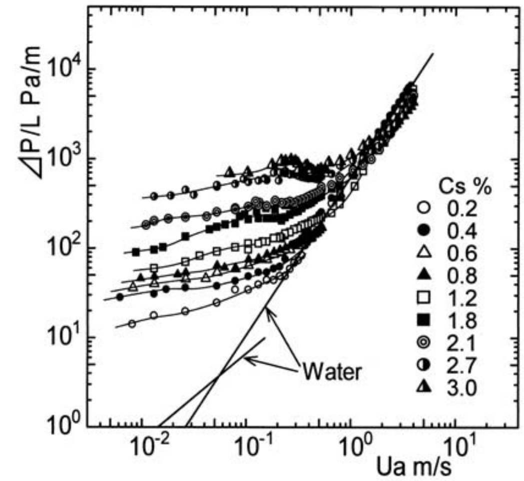


Fig. 4 Pressure loss for several fiber concentrations for $d$=22 mm.

The viscosity $\mu_w$ at the pipe wall is larger than that for water. It increases as the fiber concentration increases. Nevertheless, in the laminar flow of patterns I to III, the viscosity decreases with increasing $U_a$.

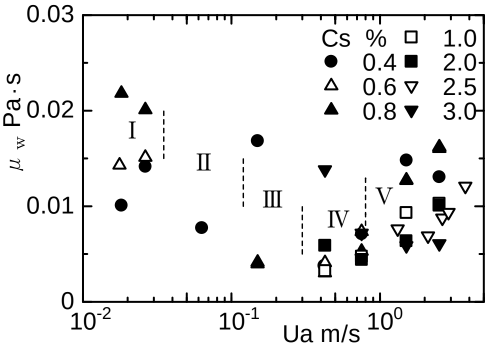


Fig. 5 Relationship between viscosity $\mu_w$ at pipe wall and mean velocity $U_a$

*A. Flow Properties at Low Velocity (Patterns I and II)*

The pulp suspension possesses so-called yield shear stress. This implies that a pressure gradient exceeding a certain magnitude is necessary for pulp suspensions to keep flowing. The $\Delta P/L–U_a$ curves in Fig. 4 are those for which the flowing state is maintained. The yield shear tress $\tau_0$ is obtained from the pressure loss when an intermittent flow occurs at a low velocity. The results are shown in Fig. 6. In Fig. 6, we show the results for the wall shear stresses, $\tau_c$ and $\tau_t$, as described later. Here, $\tau_c$ denotes the wall shear stress at which the transition to turbulent flow occurs, and $\tau_t$ is that when the flow state can be considered to be turbulent over the whole cross section. From Fig. 6, the yield shear stress $\tau_0$ can be roughly expressed using only the fiber concentration $C_s$ as

$$\tau_0 = 0.28\,C_s^{1.6} \tag{2}$$

($\tau_0$: Pa, valid for $d$=10–40 mm and $C_s$=0.3–3%).

Expression (2) is a well-known empirical equation [11]. A dependence of $\tau_0$ on the pipe diameter $d$ cannot be clearly recognized.

In pattern I, the pulp fibers become a massive flock and move as a rigid body, as shown in Fig. 3 (a). A dynamic frictional force corresponding to the yield shear stress is generated between the pulp fibers and pipe wall. When the flow rate is slightly increased, the flow pattern changes to type II. A very thin water layer begins to form annularly on the pipe wall as shown in Fig. 3 (b). Therefore, both the dynamic frictional force of the massive pulp fibers and the viscous force of the water layer act on the pipe wall simultaneously. Thereby, the pressure loss increases in proportion to $U_a$. Such behavior of pulp suspensions at a low velocity exhibits the Bingham property. In pattern II, the dynamic frictional force of the massive pulp fibers acting on the wall is softened as the water annulus is formed. Thus, the viscosity $\mu_w$ at the pipe wall becomes small compared with that of pattern I (see Fig. 5).

*B. Flow Properties at Moderate Velocity (Pattern III)*

For pattern III, the suspensions are two-phase systems in which the flowing fluid consists of a thin water annulus layer and a plug flow in the central part of the cross section. Then the flocks of pulp fibers are forced into the plug flow region as the velocity $U_a$ increases. This causes the water annulus to become thicker, as illustrated in Fig. 3 (c). Therefore, the changes in the shear rate $\gamma_w$ at the wall are less variable when $U_a$ increases and $\mu_w$ takes a minimum value relative to $U_a$ as shown in Fig. 5. That is, in the laminar flow for patterns I to III, the shear-thinning character can be recognized in the pulp suspensions in the vicinity of the pipe wall.

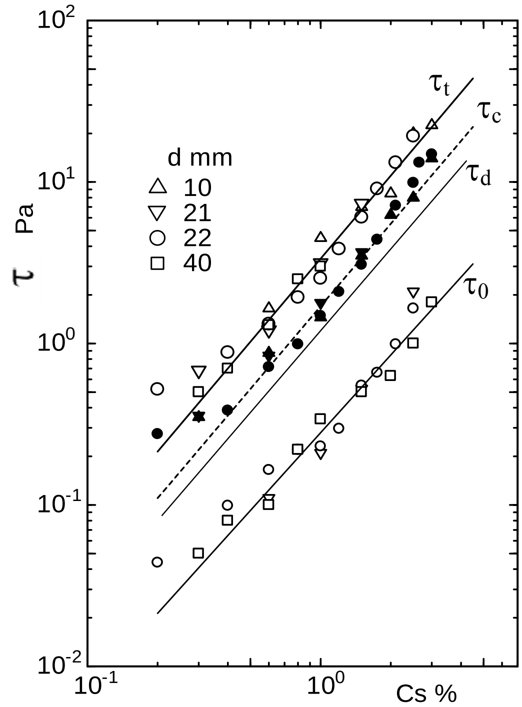


Fig. 6 Relationship between wall shear stress $\tau$ and fiber concentration $C_s$. $\tau_0$: yield shear stress, $\tau_d$: disruptive shear stress, $\tau_c$: critical shear stress, $\tau_t$: turbulent shear stress

In pattern III, the wall shear stress $\tau_{III}$ is roughly expressed as

$$\tau_{III} \approx (0.46 - 1.1)C_s^{1.7} \tag{3}$$

($\tau_{III}$: Pa, valid for $C_s$=0.4–3% and $d$=10–40 mm).

The above expression is not dependent on the pipe diameter as in the case of $\tau_0$.

*C. Flow Properties at High Velocity (Patterns IV and V)*

In pattern III, when the fluid velocity increases, the fiber concentration in the plug region also increases and the fibers there become more compressed. As a result, the thickness of the water annulus cannot increase further and a higher shear flow in the water annulus ensues. Thus, the network of flocculated pulp fibers close to the water layer starts to disintegrate (pattern IV). As a result, $\mu_w$ at the pipe wall increases as shown in Fig. 5. Nevertheless, the shear stress $\tau_{IV}$ at the wall does not change significantly and takes a value of $\tau_{IV} \approx 1.1C_s^{1.7}$. From these findings, we can conclude that the flocculated pulp fibers begin to disentangle when the shear stress $\tau_d$ is about four times the yield shear stress $\tau_0$. The dot-dashed line in Fig. 6 indicates the disruptive shear stress $\tau_d$.

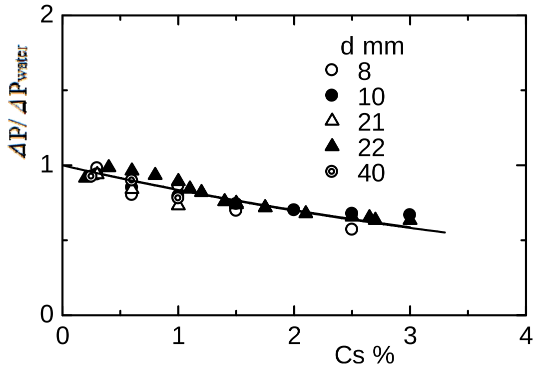

Fig. 7 Effect of fiber concentration on pressure loss in turbulent flow

With a further increase in the flow rate, turbulence occurs in the pulp suspensions and the fluid undergoes a transition from laminar to turbulent flow. Consequently, the pressure loss rapidly increases as $U_a$ increases. The critical velocity is indicated as $P_c$ in Fig. 1. The transition can be considered to start when the shear stress in the water layer exceeds a certain value. The experimental values of the critical shear stress $\tau_c$ at the pipe wall are expressed by the broken line in Fig. 6.That is,

$$\tau_c \approx 1.7C_s^{1.7} \qquad (4)$$

($\tau_c$: Pa, valid for $C_s$=0.4–3% and $d$=10–40 mm).

$\tau_c$ increases exponentially with $C_s$, similar to (2).

With a further increase in the flow rate, the pulp suspensions become turbulent over the whole cross section, and the turbulent stresses increase to disrupt the fiber networks of the plug. The flow pattern changes to type V, and the corresponding flow velocity is denoted by $P_t$ in Fig. 1. In this regime, $\mu_w$ is the turbulent viscosity, which rapidly increases with $U_a$ as shown in Fig. 6. The wall shear stress $\tau_t$ at which the flow can be considered to be thoroughly turbulent in the pipe is expressed as

$$\tau_t \approx 3.3C_s^{1.7} \qquad (5)$$

($\tau_t$: Pa, valid for $C_s$=0.4–3% and $d$=10–40 mm)

The turbulent shear stress $\tau_t$ is at least ten times the yield shear stress $\tau_0$, and the pulp fibers are dispersed almost uniformly in the pipe.

For flows in pattern V, the pressure loss $\Delta P$ is smaller than that for water, and the decrease in $\Delta P$ becomes large as $C_s$ increases as shown in Fig. 4. Thus, we compare it with that for the water in the turbulent flow region (pattern V). The results are given in Fig. 7. The pressure loss ratio can be expressed approximately as

$$\Delta P/\Delta P_{water} = \exp(-0.18C_s) \qquad (C_s\text{: \%}). \qquad (6)$$

The above expression is also unrelated to the pipe diameter $d$.

## IV. Conclusions

The flow characteristics for five regimes were examined one by one. The principal findings of this study are summarized as follows.

(1) The pulp suspensions have the properties of a Bingham fluid. The yield shear stress $\tau_0$ at the pipe wall increases with increasing fiber concentration and does not depend on the pipe diameter. $\tau_0$ can be expressed by the experimental equation (2).
(2) The flocks of the pulp fibers become disrupted by the shear stress $\tau_d$ when it exceeds about four times the yield shear stress $\tau_0$.When the wall shear stress becomes about ten times larger than the yield shear stress $\tau_0$, the pulp suspension is dispersed uniformly over the pipe cross section.
(3) The pressure loss in a turbulent flow becomes smaller than that for water with increasing fiber concentration. The rate of reduction can be approximately expressed by (5).

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