Flow Characteristics of Pulp Liquid in Straight Ducts

M. Sumida

***Abstract*—**An experimental investigation was performed on pulp liquid flow in straight ducts with a square cross section. Fully developed steady flow was visualized and the fiber concentration was obtained using a light-section method developed by the author et al. The obtained results reveal quantitatively, in a definite form, the distribution of the fiber concentration. From the results and measurements of pressure loss, it is found that the flow characteristics of pulp liquid in ducts can be classified into five patterns. The relationships among the distributions of mean and fluctuation of fiber concentration, the pressure loss and the flow velocity are discussed, and then the features for each pattern are extracted. The degree of nonuniformity of the fiber concentration, which is indicated by the standard deviation of its distribution, is decreased from 0.3 to 0.05 with an increase in the velocity of the tested pulp liquid from 0.4 to 0.8%.

***Keywords*—**Fiber Concentration, Flow Characteristic, Pulp Liquid, Straight Duct.

I. Introduction

THE purpose of this study is to investigate the fiber concentration of a pulp liquid flow and to clarify the flow characteristics in ducts with a square cross section.

Pulp liquid, in which pulp fibers are suspended in water, flows as an aggregation of pulp fibers, which repeatedly flock and disperse. Furthermore, pulp liquid is opaque, even at a low concentration, making it difficult [1] to investigate its flow characteristics. Therefore, very few attempts [2], [3] have been made to investigate them. For instance, there have been few works on the flocculation of pulp fibers, which strongly affects the quality of produced paper. Robertson and Mason [4] and Shimizu et al. [5] attempted to obtain the number of flocculations per unit length of pulp liquid flowing in tubes by measuring fluctuations in optical transmission. Davydenko and Unger [6] observed the degree of nonuniformity of the fiber concentration. However, in these studies, rough results were only obtained for the spatial distribution and/or time-dependent variation of the pulp-fiber concentration. Thus, the results in previous studies are insufficient to quantitatively discuss the dispersion of pulp fibers.

In this paper, considering the above circumstances, we deal with the problem of a pulp liquid flow in ducts with a square cross section. The flows are visualized and photographed by a high-speed camera and the fiber concentrations are evaluated by using an optical measuring method which has been developed by Sumida and Suzuki [7]. Subsequently, we obtain the distributions of time average and fluctuation of fiber concentration. Moreover, we discuss the effect of the flow velocity on the distribution and nonuniformity of the fiber concentration.

M. Sumida is with the Department of Mechanical Engineering, Kinki University, Higashi-Hiroshima, 739-2116 Japan (phone: +81-82-434-7000; fax: +81-82-434-7011; e-mail: sumida@hiro.kindai.ac.jp).

II. Experimental Apparatus and Procedure

A. Experimental Apparatus and Visualization Method

A schematic diagram of the experimental apparatus is shown in Fig. 1. The system consists of a circulating passage, a test duct, and visualization and measuring devices. The working pulp liquid was supplied to the test duct from the reservoir by a magnetic drive pump. The reservoir was equipped with a stirrer and a temperature controller. The flow rate of the pulp liquid was adjusted by a flow controlling valve and was measured by an electromagnetic flow-meter and by a volumetric method using a graduated cylinder in the downstream part. The test ducts had a side d of 15 or 20 mm and a length of 2800 mm with a wall thickness of 5 mm. The ducts were made of acrylic plates.

The flow was visualized by a light-section method. The pulp liquid flowing on the horizontal plane including the duct axis was illuminated by a sheet of light of 1 mm thickness from two metal halide lamps (150 W). The illuminated plane was photographed from above using a high-speed camera (Photron FASTCAM-1024 PCI) and a digital camera (Nikon D100). The obtained images were processed using a personal computer to evaluate the fiber concentration. The evaluation technique has been described in detail in the author's recent work [7].

The origin of the coordinate system is the center of the cross section. The x and y axes are in the downstream and lateral horizontal directions, respectively. Before the visualization experiment, preliminary measurements were executed to determine the pressure loss, and the relation between the pressure loss and flow rate was obtained.

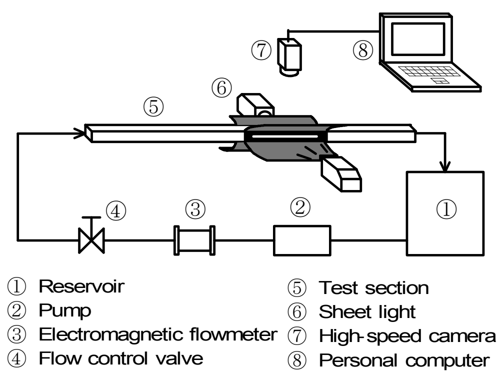


Fig. 1 Schematic diagram of experimental apparatus

TABLE 1
PROPERTIES OF PULP FIBERS

Freeness (CSF)	396 cc
Water retention value	1.58
Arithmetic average length	0.50 mm
Length-weighted average length	0.70 mm
Mass-weighted average length	1.00 mm
Coarseness	0.072 mg/m

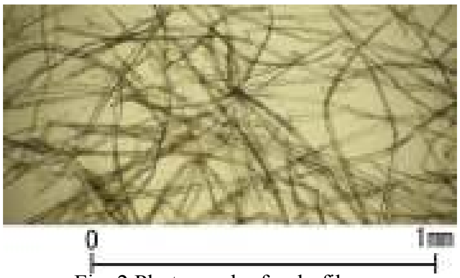


Fig. 2 Photograph of pulp fibers

B. Test Pulp Liquid

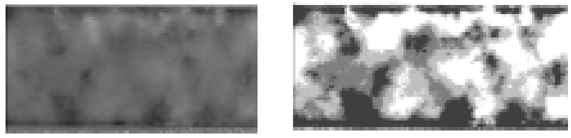
The working pulp liquid was a Kraft pulp (LBKP: Laubholz Bleached Kraft Pulp), which is the most commonly used pulp for high-quality paper. The raw material was made mainly from broadleaf trees. The main physical properties of the pulp fibers are shown in Table I. A photograph of the fibers employed in this study is presented in Fig. 2.

The experiments were performed under pulp concentrations of C_S = 0.2 – 3.0%, where concentrations of C_S = 1% or less are used in current papermaking machines.

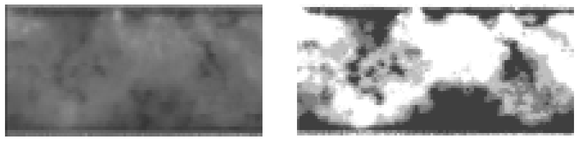
III. RESULTS AND DISCUSSION

A. Pulp-Fiber Flow Patterns

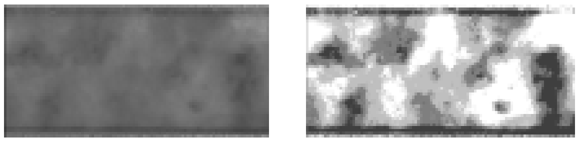
The changes in the concentration distribution with the flow rate are demonstrated in Fig. 3 [7], where C_S=0.6% for the tested pulp liquid. The four-level distributions on the right of Fig. 3 are formed with reference to the value of C_{rms} for the low mean velocity U_a=0.025 m/s. Here, C_{rms} is the standard deviation of the distribution $C(x, y)$ of the fiber concentration. The patterns of pulp-fiber concentration in the flow can be classified into five types, patterns I–V, as illustrated in Fig. 4. A schematic profile of the velocity is attached to each pattern. This classification shows the dispersion state of the pulp fibers in more detail than the classification hitherto proposed. The previous classification method is based on the relation between the pressure loss and the flow rate [2], [8], where the flow characteristics are classified into three types: (i) plug flow, (ii) mixed flow, and (iii) turbulent flow. The relation between the pressure loss per unit length, $\Delta P/L$, and the mean velocity in our experiment is shown in Fig. 5 for the duct of d=20 mm. The solid lines in Fig. 5 indicate the results for water. Moreover, the correspondence of the $\Delta P/L–U_a$ curve in Fig. 5 with patterns I –V is shown in Fig. 6. Fig. 7 also shows the classification for



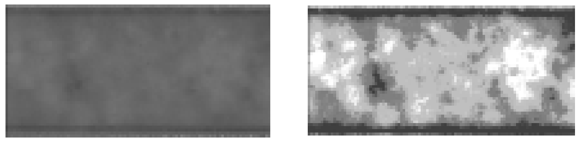
(a) Pattern I (Ua = 0.025 m/s)



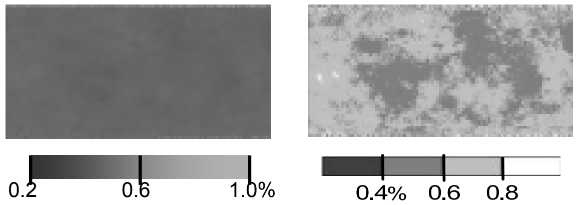
(b) Pattern II (Ua = 0.075m/s)



(c) Pattern III (Ua = 0.20m/s)



(d) Pattern IV (Ua = 0.38m/s)



(e) Pattern V (Ua = 3.5m/s)

Fig. 3 Influence of average velocity on the distribution of fiber concentration (Cs = 0.6%). Left and right figures show the distributions and four-leveled ones of fiber concentration, respectively. Pulp-suspension flows in the right direction

the pulp liquid flow with C_S= 0.2 – 3%. The solid lines demarcating patterns are drawn in accordance with the classification method described later and are obtained from the experimental results for the pressure loss together with flow observation. As the pulp-liquid concentration C_S increases, the mean velocity at which the pattern shifts to the next one becomes larger. Referring to the previous classification [2], [8], patterns I and II correspond to plug flow, patterns III and IV are equivalent to mixed flow, and pattern V corresponds to turbulent flow.

In the following, we take the result for C_S=0.6% as the representative result. We discuss the effect of the mean velocity on the dispersion state of the flowing pulp fibers.

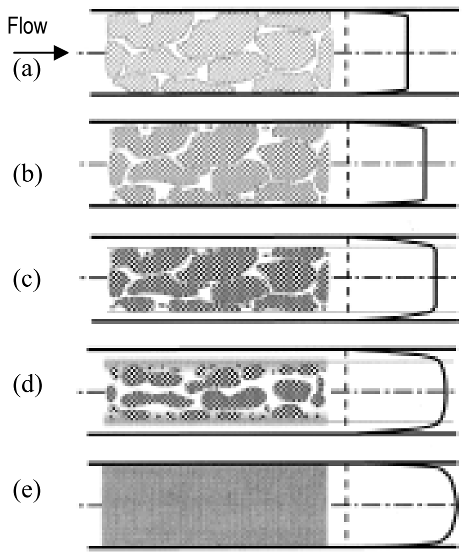


Fig. 4 Schematic diagrams of typical flow patterns of pulp-suspension. (a) Pattern I: Plug flow with strong interaction between fiber and duct-wall, (b) Pattern II: Plug flow with hydrodynamic shear and fiber-wall interaction, (c) Pattern III: Plug flow with the water annulus in laminar shear, (d) Pattern IV: Mixed flow with fiber/water annulus and transitional flow from laminar to turbulent, (e) Pattern V: Turbulent flow with distributed pulp-fibers

B. Effect of Mean Velocity on Flow Pattern of Pulp Fibers

For a lower flow velocity ($U_a \leq 0.035$ m/s: Figs. 3(a) and 4(a)), flocculations of pulp fibers exist throughout the duct and move in the downstream direction with uniform velocity as a rigid body (pattern I). Fibers and flocculations touch the wall of the duct, and thereby a frictional force is generated between the pulp fibers and the duct wall. The dynamic frictional force does not change significantly with the flow velocity. Consequently, the pressure loss is almost constant in this regime, as can be seen in Figs. 5 and 6. The effect becomes more noticeable at high concentrations [9].

When the flow rate is increased slightly ($U_a \approx 0.035$ m/s), a very thin water layer with a low concentration of fibers is formed on the duct wall. In this layer, with increasing flow velocity U_a, flocks protruding from aggregations and/or flocculations of pulp fibers are observed to break off and these small fragments roll along the wall surface. In this pattern (pattern II; $U_a = 0.035 - 0.09$ m/s; Figs. 3(b) and 4(b)), both the dynamic frictional force of massive pulp fibers and the viscous force of the water layer act on the duct wall. As a result, the pressure loss increases slightly in proportion to U_a (see Fig. 6). For a moderate flow rate, small fragments lying sporadically in the neighborhood of the wall rotate owing to the shear flow in the water layer. The rotation of the fragments exerts a lift on them, and as a result they are forced towards the duct axis. Then, the rolling flocks separate from the wall surface and are incorporated in the adjacent flocculations embedded in the plug flow. Thus, the fiber concentration of the water layer is sufficiently reduced for an annular water layer to be formed on the wall. The water annulus becomes thicker as U_a increases. Therefore, the flow is divided into two regions (U_a = 0.09 – 0.27 m/s; Figs. 3(c) and 4(c): pattern III). One is the water annulus near the wall with a low fiber concentration. The other is a plug flow region in the central part of the cross section, where the flocculations of pulp fibers are narrowed slightly. In this regime, although the velocity in the plug region increases with increasing flow rate, the water annulus also becomes thicker as mentioned above. As a result, even when the flow rate increases, the velocity gradient at the wall does not change significantly and, accordingly, the pressure loss shows little change. For a high-concentration pulp liquid, the pressure loss in this regime actually decreases with increasing flow rate, as can be seen in Figs. 5 and 6.

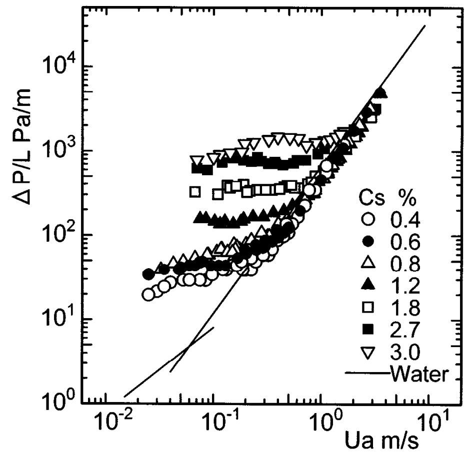


Fig. 5 Pressure losses for several concentrations of pulp-suspension

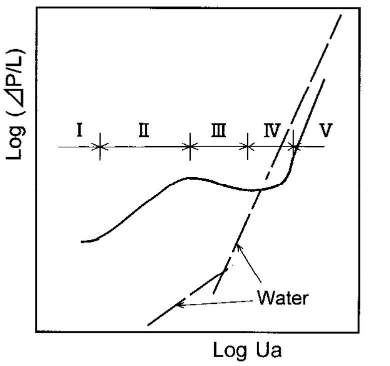


Fig. 6 Relationship between flow regime and pressure-loss curve illustrated logarithmically as a function of velocity

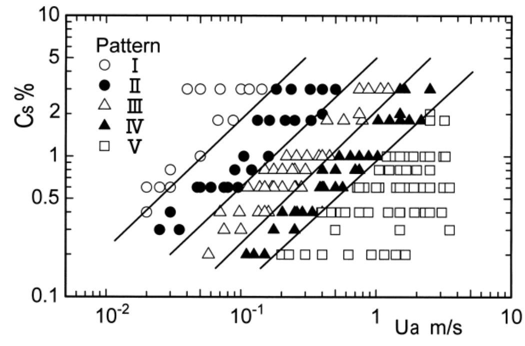
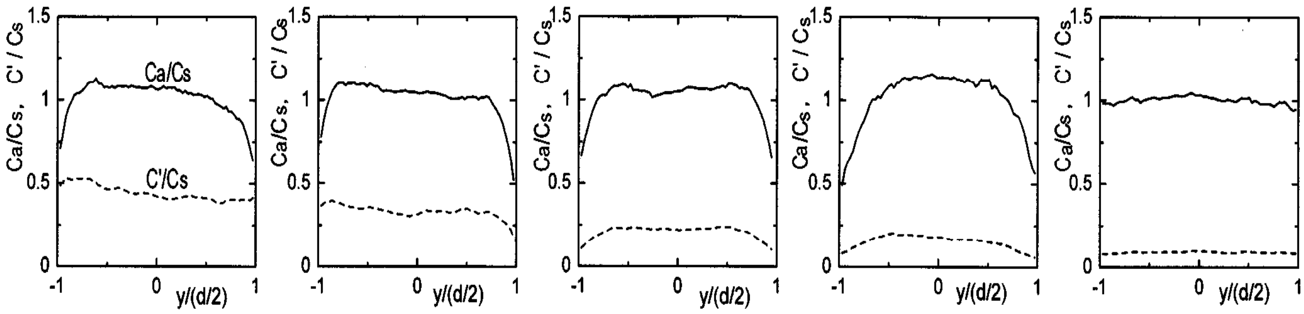


Fig. 7 Classification of flow patterns for various fiber-concentrations and velocities



(a) Pattern I $Ua = 0.025$m/s | (b) Pattern II $Ua = 0.063$m/s | (c) Pattern III $Ua = 0.20$m/s | (d) Pattern IV $Ua = 0.40$m/s | (e) Pattern V $Ua = 2.5$m/s

Fig. 8 Distributions of fiber concentration on y-axis ($Cs = 0.6\%$)

When the flow rate is increased further, the velocity gradient of the flow in the water annulus becomes steep. The strong shearing stress that occurs causes the flocculated pulp fibers adjacent to the water layer to disintegrate and disentangle (U_a = 0.27–0.6 m/s; Figs. 3(d) and 4(d); pattern IV). Moreover, the flow in the water annulus also begins to be disturbed, and more pulp fibers become scattered in this layer. Thus, as the flow rate increases, the transition to turbulent flow in the water annulus proceeds, causing the fiber concentration in the layer to increase gradually. Therefore, the pressure loss begins to increase again with the flow rate and it approaches a value proportional to the square of the mean velocity, as shown in Figs. 5 and 6.

When the mean velocity becomes large ($U_a \cong 0.6$ m/s) and the flow reaches a fully developed turbulent state, flocculations form even smaller aggregates owing to the turbulent mixing motion. Hence, the pulp fibers are scattered over the entire cross section, resulting in the fiber concentration having a uniform distribution (Figs. 3(e) and 4(e); pattern V). In this regime, the pressure loss increases with U_a in a similar manner to that for a pure water flow. However, it is slightly smaller than that for the water flow, as shown in Fig. 5.

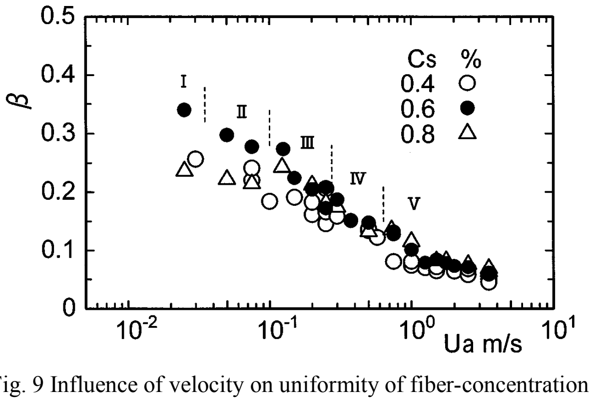


Fig. 9 Influence of velocity on uniformity of fiber-concentration

C. Concentration Distribution on y-Axis and Nonuniformity

Fig. 8 shows the distributions of time-averaged concentration C_a and the fluctuations of the concentration C' on the y-axis. Moreover, the values of $\beta = C_{rms}/C_S$, which represents the degree of nonuniformity of the fiber concentration, are shown in Fig. 9. The broken lines in Fig. 9 indicate the classification of flow patterns for C_S =0.6%. These figures also demonstrate the distinct features in each pattern.

For pattern I, the flocculations touch the duct wall, and small regions free of fibers exist in the neighborhood of the wall. On the other hand, in the central part of the cross section, the fiber concentration has a distribution clearly indicating the presence of flocculations. Hence, the value of β is large, and the fluctuation C' is high near the wall and small in the central plug region, as shown in Fig. 8(a). In pattern II, C_a and C' have small values in the water layer with a low fiber concentration formed on the wall (Fig. 8(b)). For pattern III, a water annulus with a low C_a becomes thick with increasing mean velocity, and thereby flocculations are pushed toward the plug region. This causes C_a to increase slightly and C' to decrease in the water annulus and the plug region (Fig. 8(c)).

For pattern IV, where the flow is in a transitional state, the C_a distribution becomes parabolic since the flocculated pulp fibers adjacent to the water annulus come apart and disentangle. In addition, the fluctuation C' decreases in the entire cross section (Fig. 8(d)). In pattern V, corresponding to turbulent flow, the distributions of C_a and C' are further flattened (Fig. 8(e)). Consequently, the nonuniformity of the fiber concentration β gradually decreases as U_a increases and is reduced to about 0.05 in pattern V as demonstrated in Fig. 9.

IV. Conclusions

The characteristics of the pulp liquid flow in ducts are investigated by applying a light-section method of obtaining the distribution of the fiber concentration. The principal findings of this study are summarized as follows.

(1) The flow of pulp liquid in a duct is classified into five patterns according to the flow mechanism and the characteristics of the fiber-concentration distribution. This classification is different from the previous classification of flows, that is, into plug, mixed, and turbulent flows.

(2) The relative value $\beta = C_{rms} / C_S$, introduced as an index to express the nonuniformity of the fiber concentration, decreases from approximately 0.3 to 0.05, regardless of the value of C_S, in the measurement range of $C_S = 0.4 - 0.8\%$, as the mean velocity increases.

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