A Study on Flow Characteristics of Pulp Suspension Flow*

- Measurement of Turbulence Intensity and Fiber

Concentration Unevenness -

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In order to examine the relationship between the turbulence intensity and the fiber concentration unevenness in the flow of pulp suspension, these quantities were measured in a duct with various types of turbulence generators installed at the duct inlet. The turbulence intensity of suspension flow was measured by two small pressure transducers and the concentration unevenness was measured as the intensity fluctuation of light transmitted through the pulp suspension in the duct section. The results show that the concentration unevenness is inversely related to the turbulence intensity. It is also found that there is a time delay in change of the concentration unevenness due to the turbulence. It is believed that the test results provide useful information on development of improved paper-machine headboxes.

Key Words : Non-Newtonian Fluid, Flow Measurement, Pulp Suspension, Turbulence Flocculation, Impact probe, Papermachine Headbox

1. Introduction

In a pulp slurry where pulp is suspended in water (hereafter called "pulp suspension"), the pulp tends to flocculate with fibers locally aggregated, causing an unevenness of the fiber concentration in the flow. This concentration unevenness is so related to the flow characteristics that it is much more significant when the flow velocity is lower or the concentration is higher^{1),2)}, and poses an interesting problem in terms of the turbulent flow of a non-Newtonian fluid.

In the papermaking industry, minimizing the fiber concentration unevenness of pulp suspension in the process is a key point to manufacture of quality papers. Therefore, clarifying the flow characteristics of pulp suspension is one of the most important problems in the art of papermaking. In the papermaking process, the pulp suspension is discharged in the form of a thin two-dimensional jet from a nozzle called a headbox onto an endless wire-screen belt, on which the wet web of paper is formed and drained, then goes to continuous stages of presses and dryers. The fiber arrangement condition of paper as manufactured is called the sheet formation, which is affected mainly by the unevenness in weight/area distribution. The appearance, pleasantness to touch, printability, strength, etc. of paper are related to the sheet formation, and this term is used to directly express the

general quality of paper. Recently, the operating speed of paper machines is much increased, and the time for formation of the wet web of paper and water draining on the wire-screen belt is considerably reduced. Under these circumstances, the fiber concentration unevenness in the pulp suspension in the headbox and the conditions of jet from the headbox influence the sheet formation more significantly. Since it seems that no analysis has been made on the flow conditions of pulp suspension with respect to the sheet formation, the authors have made a simplified approach to this problem which is described below.

Figure 1 shows a longitudinal section of the jet of pulp suspension from a head box. Let the thickness-mean fiber concentration at a cross section of the jet be C_J (kg/m^3), the thickness of the jet be H_J (m), the thickness-mean jet velocity be U_J (m/s) and the running speed of the wire-screen belt be V (m/s), then the per-unit-area mass of fibers deposited on the wire-screen belt, W (kg/m^2), is given by

Fig. 1 Jet of pulp suspension from headbox.

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$$W = C_J H_J U_J / V \quad \dots\dots\dots (1)$$

With respect to the time, the above quantities except V can be separated into the mean components of $\bar{W}$, $\bar{C}_J$, $\bar{H}_J$ and $\bar{U}_J$ and the variation components of w , c_J , h_J and u_J , respectively, and we have

$$\bar{W} + w = (\bar{C}_J + c_J)(\bar{H}_J + h_J)(\bar{U}_J + u_J) / V \quad \dots\dots\dots (2)$$

By squaring Eq. (2) and averaging for the time, we have

$$\begin{aligned} \bar{W}^2 + \bar{w}^2 = & \frac{\bar{C}_J^2 \bar{H}_J^2 \bar{U}_J^2}{V^2} \left(1 + \frac{\bar{c}_J^2}{\bar{C}_J^2} + \frac{\bar{h}_J^2}{\bar{H}_J^2} + \frac{\bar{u}_J^2}{\bar{U}_J^2} \right. \\ & \left. + \frac{4\bar{C}_J \bar{h}_J}{\bar{C}_J \bar{H}_J} + \frac{4\bar{h}_J \bar{u}_J}{\bar{H}_J \bar{U}_J} + \frac{4\bar{C}_J \bar{u}_J}{\bar{C}_J \bar{U}_J} \right) \quad \dots\dots\dots (3) \end{aligned}$$

In Eq. (3), the third and higher terms of the variation components are ignored. If the variation components are independent of each other, then Eq. (3) is rewritten as follows:

$$\left(\frac{\sqrt{w^2}}{\bar{W}} \right)^2 = \left(\frac{\sqrt{c_J^2}}{\bar{C}_J} \right)^2 + \left(\frac{\sqrt{h_J^2}}{\bar{H}_J} \right)^2 + \left(\frac{\sqrt{u_J^2}}{\bar{U}_J} \right)^2 \quad \dots\dots\dots (4)$$

That is, the variation factor of W is given as the sum of the squares of the variation factors of C_J , H_J and U_J . If we assume that the fiber distribution on the wire-screen belt is unaffected by the subsequent short-time draining and paper web formation, then the condition necessary to improve the paper quality is, according to Eq. (4), to minimize the three variation factors on the righthand side. These factors are related to the turbulence in the flow in the headbox, and it is generally observed that the larger the turbulence, the smaller the first term on the righthand side of Eq. (4), but the larger the second and third terms. In other words, the variation in the fiber concentration and the variations in the jet thickness and velocity are in a conflicting relationship with respect to the turbulence in flow. Therefore, in order to realize a headbox that minimizes $\sqrt{w^2}/\bar{W}$, which is most important in improving the formation of paper, more knowledge on the flow characteristics of pulp suspension is necessary.

The research works on the flow of pulp suspension made so far include reports on friction losses in pipes and flow velocity distributions in pipes^{3),4),5)}, and some measurement results on fiber concentration variations^{6),7)}. For the intensity of turbulence in flow, while the results when the fiber concentration is low are reported^{8),9)}, to the authors' knowledge, no quantitative examinations on it, such as its correlation with the concentration variation, are reported. In view of the above, we have measured the turbulence intensity and fiber concentration variation in pulp suspension flowing in a duct in an effort to clarify quantitatively the relationship between them.

2. Test Apparatus and Test Method

2.1 Test apparatus. Figure 2 shows an outline of the test apparatus used in measurements. Water or pulp suspension is pumped up from the mixing tank to the head tank, from which it flows down the pipeline and the measuring section and returns to the mixing tank. The section-mean flow velocity U_m at the measuring section is determined from the indication of the electromagnetic flowmeter provided on the downstream side of the measuring section. The head tank has an overflow weir to keep the liquid level constant. The dimensional detail of the measuring section and adjacent parts is given in Fig. 3. The measuring section is a duct of clear acrylic, which has a rectangular cross-section of 20 mm wide by 100 mm long and a length of 750 mm. The upstream approach piping has a large cross-sectional area and a smoothly narrowed down connection to the measuring section to keep the turbulence in flow in this region minimum. The coordinate system, as shown in Fig. 3, takes the center of the inlet cross-section of the measuring section as the point of origin, from which X-axis extends vertically downward, Y-axis horizontally in parallel with the shorter sides, and Z-axis also horizontally in parallel with the longer sides. Table 1 shows the shapes of four different turbulence generators used in measurements which are located immediately above the measuring section inlet: S for straight type for smooth area reduction to the duct flow, O-15 and O-10 for two-dimensional orifices of 15/20 and 10/20 in area reduction, and D30°-10 for two-dimensional diffuser block of 30° in opening angle.

Fig. 2 Outline of test apparatus.

2.2 Measurement of flow velocity and turbulence intensity. If a sensor, such as a pitot tube or hot-film velocity meter, is placed in a flow of pulp suspension, suspended fibers will deposit and accumulate on the tip of the sensor, making an accurate measurement of flow velocity difficult even if the fiber concentration is low. While the use of Laser-Doppler velocity meter, a non-contact type velocity meter, in measurements where the concentration is very low is reported, its use in cases where the concentration is high poses a problem of reduced S/N ratio due to light scattering by fibers.^{10),11)}

In this study, a simpler method is used in which the total pressure of the flow and the static pressure are separately measured, then the mean and variation components of the flow velocity are estimated from the difference between

them. The measuring setup is shown in Fig. 4. The total pressure probe uses a miniature pressure transducer of 3 mm in diameter to sense the pressure. This sensor is set on the end of a stainless steel tube, and an acrylic ring of 6 mm O.D. is placed around the sensor to prevent the accumulation of fibers on the sensing surface. When the sensing surface of the probe is placed in and against the flow of pulp suspension, there occurs a small stagnation on the sensing surface. The sensor senses a change of this stagnation due to turbulence in the flow and, at the same time, this stagnation prevents the accumulation of fibers on the sensing surface. The static pressure probe also uses an identical pressure transducer, which is mounted in the wall of the measuring section at the same position in the X-axis direction as the total pressure probe.

While there are examples of measurement of velocity change with a total pressure probe only where variations in the static pressure are negligible, the following consideration is necessary when the measurement is made with two probes. Let the dynamic pressure and static pressure on the sensing surface of the total pressure probe in the flow be P_D and P_S , the indication of the total pressure probe be P_T , and the indication of the static pressure probe be P_{SW} , then the difference in indication between these probes is

$$P_T - P_{SW} = P_D + P_S - P_{SW} \\ = (\rho/2)(\bar{U} + u)^2 + (\bar{P}_S - \bar{P}_{SW}) \\ + (p_{sh} - p_{shw}) + (p_s - p_{sw}) \dots \dots \dots (5)$$

where: $\bar{U}$ = time-mean component of flow velocity,

u = variation component of flow velocity,

$\bar{P}_S, \bar{P}_{SW}$ = time-mean static pressure measured by respective probes,

p_{sh}, p_{shw} = variation components of P_S and P_{SW} due to change in liquid level in head tank,

p_s, p_{sw} = variation components of P_S and P_{SW} due to other causes,

ρ = density of pulp suspension.

Table 1. Shapes of turbulence generators.

Name	Diffuser	Orifice		Straight
Symbol	D30°-10	0-10	0-15	S
Figure of X-Y Section
B=20mm

Fig. 3 Dimensional detail of measuring section.

Fig. 4 Measurement of flow velocity and turbulence intensity.

Since the second and third terms on the righthand side of Eq. (5) can be treated as zero, the output ($P_T - P_{SW}$) of the differential amplifier is given as follows:

$$P_T - P_{SW} = (\rho/2)(\bar{U} + u)^2 + (p_s - p_{sw}) \quad \dots (6)$$

That is, the differential amplifier output indicates the sum of the dynamic pressure due to flow and the difference in static-pressure variation component due to flow between the total and static pressure probes. If we assume that the second term on the righthand side of Eq. (6) is much smaller than the first term, then the flow velocity can be approximated as follows:

$$\begin{aligned} \bar{U} + u &= \sqrt{\frac{P_T - P_{SW}}{\rho/2}} \sqrt{1 - \frac{p_s - p_{sw}}{P_T - P_{SW}}} \\ &\approx \sqrt{\frac{P_T - P_{SW}}{\rho/2}} \quad \dots (7) \end{aligned}$$

Figure 5 shows the output signal of the probes which are observed on an oscilloscope. The horizontal time sweep is 20 ms/div., and the vertical one is the pressure above the atmospheric pressure, the pressure when the flow is stopped being 100%. In each oscilloscope representation, the upper trace is the output of the total pressure probe and the lower trace is the output of the static pressure probe. The difference between the 100% line and the output of the total pressure probe corresponds to the head loss due

Fig. 5 Output of pressure transducer probes.

to flow, and the difference in output between the probes approximately represents the dynamic pressure head. In the case of Type S inlet where the turbulence in flow is considered relatively low, the waveforms of the total pressure and static pressure are in a fairly good agreement in shape, indicating that the variation component of the static pressure due to a change in the liquid level in the head tank is dominant and the variation component of the dynamic pressure is small. In the case of Type O-10 inlet, on the other hand, the variation component of the total pressure is much larger than that of the static pressure, and they greatly differ in waveform. This suggests that in addition to irregular fluctuations of the liquid level in the head tank, there is a large variation component in the dynamic pressure.

With the validity of the approximation of Eq. (7) confirmed as above, the output ($P_T - P_{SW}$) of the differential amplifier is put through a square root amplifier to obtain an approximately value of the flow velocity at the sensing surface of the total pressure probe. The square root amplifier output is further decomposed into the time-mean value $\bar{U}$ and the standard deviation u' of the variation component, and $u'/\bar{U}$ is used as the turbulence intensity.

Figure 6 compares the frequency spectrum of the turbulence intensity $u'/\bar{U}$ measured by the pressure transducer method with that by the hot-film method. While the turbulence intensity determined by the pressure transducer method is much lower in a higher frequency region than that by the hot film method, the difference in result between these methods is small in a lower frequency region. In short, the pressure transducer method, though its sensitivity at higher frequencies is low, can determine fairly well the variation component of the flow velocity, or the turbulence in flow.

Fig. 6 Frequency spectrum of turbulence intensity.

2.3 Measurement of fiber concentration unevenness. In this study, the fiber concentration unevenness is determined by measuring the intensity of light transmitted through the measuring section and received by a very small area. Therefore, this is equivalent to measuring a change of the thickness-mean fiber concentration with the time. Figure 7 shows the measuring setup used. The laser light is directed from one side to the measuring section, in which light is scattered and attenuated by the pulp suspension and then received by a photo cell embedded in the other side wall of the section. Figure 8 shows a change of the photo cell output when the mean fiber concentration by weight C_m of pulp suspension circulated in the apparatus is changed. When the concentration is low, the light absorption by pulp suspension is dominant and Lambert-Beer's law holds. However, with an increase of concentration, the effect of light scattering by fibers becomes more significant and an exponential relationship holds between the fiber concentration and the intensity of transmitted light in a range of $C_m = 0.1$ to 0.5 wt.%. Therefore, the photo cell output is put through an exponential amplifier to have a linear C_m -output relationship as shown in Fig. 9 within the above concentration range. Special consideration has also been made in selection of the sensor components and circuitry to have a sufficiently quick response. The concentration sensor signal is proportional to the thickness-mean fiber concentration C_Y (%) of the flowing pulp suspension and, as in the flow velocity signal, can be decomposed into the time-mean component $\bar{C}_Y$ and the variation component c_Y . Figure 10 shows waveforms of c_Y measured at $U_m = 1$ and 2 m/s. Let the standard deviation of c_Y be c_Y' , then the fiber concentration unevenness is given as $c_Y'/\bar{C}_Y$. The measurement positions are at $Z = 0$ mm and at 10 to 40 mm intervals in the X-axis direction of the measuring section for each type of inlet shape.

Fig. 7 Measurement of fiber concentration unevenness.

The pulp suspension used is a 0.44% suspension of kraft pulp, which is close to the concentration actually used in papermaking. The results of pipe pressure loss measurement with this pulp suspension indicate that the loss is much larger than with water at low flow velocities of less than about 1 m/s, but is smaller than with water at higher flow velocities, exhibiting flow characteristics different from those of Newtonian fluids.¹⁴⁾

Fig. 8 Photo cell output voltage.

Fig. 9 Calibration results of fiber concentration sensor.

Fig. 10 Variation component of concentration sensor signal.

3. Test Results and Discussion

3.1 Mean velocity distributions in measuring section. The velocity distribution along Z-axis at each cross-section is measured by traversing the total pressure probe in Z-axis directions with $Y = 0$ mm. The velocity distribution at the downstream end is still uniform within a range of $|Z| \leq 30$ mm. Therefore, it is presumed that the widthwise or Z-axis distributions of the time-mean fiber concentration and flow velocity at a given cross-section are uniform within the above range. In view of this, the subsequent measurements were made at $Z = 0$ mm with the obtained results treated as representative flow data at the cross-section measured.

3.2 Measurement results of turbulence intensity. Figure 11 shows an X-axis direction distribution of the turbulence intensities $u'/\bar{U}$ at the cross-sectional center ($Y = 0$ mm, $Z = 0$ mm) of the measuring section for various types of inlet shapes or turbulence generators installed at position of $X/B = 0$. Here, X/B is a non-dimensional distance with the distance X divided by the thickness of flow $B = 20$ mm. While the results given in Fig. 11 were obtained at $U_m = 3$ m/s, the value of $u'/\bar{U}$ was almost the same independently of U_m , provided U_m was not less than 1 m/s. Except for Type S, the turbulence intensity shows a steep rise from the inlet position, reaches maximum at $X/B = 5$ to 7.5, then smoothly tapers down toward the downstream side. It is further presumed that in all cases, the turbulence intensity approaches a single ultimate value at sufficiently downstream positions, and this ultimate value is considered equal to the turbulence intensity in a well-developed flow between parallel flat plates.

Figure 12 compares the turbulence intensity measurement results when the fluid is pulp suspension with those when it is water, for Types S and 0-10 of inlet shapes. While almost no difference is seen between the results with water and with pulp suspension when Type 0-10 is

used, the difference between them is very large when Type S is used. For example, an increase of the turbulence intensity starts from a position close to the inlet in the case of water, whereas it occurs only after $X/B = 25$ in the case of pulp suspension. When Type 0-10 is used, the turbulence is mainly due to the presence of an orifice at the inlet and, in the case of such a strong turbulence, there seems to be no appreciable difference in turbulence intensity between the water and the pulp suspension of the concentration used. When Type S is used, the turbulence occurs from the walls and, within the range of measurements, the cross-sectional distribution of flow velocities and the turbulence from the walls are considered to be still in the process of development, thus the non-Newtonian behavior of pulp suspension flow appearing as the difference in the results.

3.3 Measurement results of fiber concentration unevenness. Figure 13 shows an X-axis direction distribution of the fiber concentration unevenness $c'_y/\bar{C}_y$ for various cases. The distribution differs depending on the type of inlet shape and the flow velocity. For a given U_m value, the concentration unevenness is always largest when Type S is used, and is smallest when Type 0-10 is used. For a given type of inlet shape, the higher the section-mean flow velocity, the lower the concentration unevenness.

The effect of the inlet shape on the concentration unevenness distribution is seen as follows. When Type 0-10 or D30°-10 is used, the concentration unevenness shows a steep decrease from the inlet position, reaches minimum at $X/B = 5$ to 10, then gradually increases toward the

Fig. 11 X-axis direction distribution of turbulence intensity.

Fig. 12 Comparison in turbulence intensity between water and pulp suspension.

downstream side. When Type S is used, except when $U_m = 0.5$ m/s, the concentration unevenness shows a gradual decrease from the upstream to the downstream side. When Type 0-15 is used, the distribution is somewhere between the first (0-10 or D30°-10) and second (S) cases.

The value of the concentration unevenness obtained for the four different inlet shapes become closer to each other as X/B increases. This tendency is more significant when U_m is higher. However, since X/B is limited in measurement, it is not possible to ascertain whether the results converge to a single value or reach different ultimate values with an increase of X/B . In either case, it is obvious that the concentration unevenness is affected by the turbulence intensity in a region where the former changes with X/B . A further discussion is made in the next subsection.

Fig. 13 X-axis direction distribution of fiber concentration unevennesses.

3.4 Relationship between turbulence intensity and fiber concentration unevenness. Figure 14 shows a plot of the fiber concentration unevenness on ordinate and the turbulence intensity on abscissa for various cases. The arrows in the figure indicate the direction from the upstream to the downstream side. The gradient of the curves in general is negative, indicating an inverse correlation between the turbulence intensity and the concentration unevenness. It is noted that the change of concentration unevenness takes a different path depending on whether the turbulence intensity is increasing or decreasing. When Type 0-15 is used, in particular, the concentration unevenness continues to decrease even after the transition point of the turbulence intensity change from increase to decrease. This suggests that the concentration unevenness changes with the turbulence intensity with a time-delay.

Also, it seems that there holds a common relationship between the turbulence intensity and the concentration unevenness for all types of flows. This suggests that there exists an equilibrium concentration unevenness for a steady-state turbulence intensity, though it is not clear if the same equilibrium concentration unevenness will result regardless of whether the turbulence intensity has reached a steady-state through an increasing process or through a decreasing process. However, if we assume an equilibrium concentration unevenness for a given turbulence, then a change with a time-delay of the concentration unevenness may be given as a function of the difference between the actual concentration unevenness and the assumed equilibrium concentration unevenness.

Fig. 14 Relationship between turbulence intensity and concentration unevenness.

In the papermaking process, as already mentioned, it is necessary to reduce both the turbulence intensity and concentration unevenness in the jet of pulp suspension from the headbox to produce quality paper. The fact as observed in our experiments that there exists a temporary condition where both the turbulence intensity and the concentration unevenness are low due to a delayed change of the concentration unevenness may be utilized to realize the optimum conditions of flow from the headbox.

4. Conclusions

The following is a summary of the findings:

(1) The desirable conditions of pulp suspension jet from the headbox of the paper machine are to minimize both the concentration unevenness and the jet thickness variation. These two are, however, conflicting with each other with respect to the turbulence in the flow.

(2) The turbulence intensity in the pulp suspension flow was measured by the pressure transducer probe method. The results were essentially the same as those obtained on the water flow where the turbulence intensity was sufficiently high.

(3) The concentration unevenness, the variation of the thickness-mean fiber concentration of pulp suspension flow, was measured by the light transmission method, showing that the concentration unevenness is affected by the flow velocity and the type of turbulence generator.

(4) Examination of the measurement data for the relationship between the turbulence intensity and the concentration unevenness reveals that the concentration unevenness is inversely related to the turbulence intensity. It is also found that there is a time-delay in change of the concentration unevenness with the turbulence intensity and, utilizing this time-delay, it is possible to have a condition where both the concentration unevenness and the turbulence intensity are reduced.

It is believed that the above test results provide useful information on development of improved paper-machine headboxes. Finally, the authors wish to express their thanks to Prof. Ikuo Nakamura, Department of Mechanical Engineering, Faculty of Engineering, Nagoya University.

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