High consistency sheet forming

Part 1: Research and development of headboxes

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ABSTRACT *RAPPT conducted a series of successful trials for producing printing and writing paper at 3% headbox consistency and high speed. Part 1 describes the fundamental research on the hydrodynamic behavior of a high-consistency pulp suspension in relation to its consistency unevenness. Flow in a channel of the saw-blade type and its modifications were measured to find the optimum shape. Image analysis was used to quantify the jet surface conditions, and the results coincided well with the sheet formation index of the paper samples obtained in the pilot plant tests. The headbox developed offers useful technical know-how for the low-consistency sheet-forming process as well. Achievements in the pilot plant will be presented in Part 2.*

KEYWORDS
Consistency
Equipment
Fibers
Formation
Headboxes
Image analysis
Turbulence

RAPPT was established in September 1982 by 18 major papermakers and eight machinery manufacturers for the purpose of revitalizing the Japanese pulp and paper industry and to save natural resources. The project is reputed to be the first joint work bridging related industries.

Here, we will limit our discussion specifically to high-consistency sheet forming. Improving the headbox is essential for resolving various problems caused by firm flocs of fibers in the high-consistency pulp suspension. In addition to the basic requirements such as a uniform fiber dispersion and a stable jet, the high-consistency headbox must be able to maintain intense turbulence under a reduced flow volume, to prevent the flow channel from plugging, and to reduce pressure loss. A saw-blade headbox (**Fig. 1**) was introduced, after thorough measurement of consistency unevenness in the flow of a high-consistency pulp suspension.[1]

Elementary analysis

Figure 2 is the outline of the elementary experimental device. Starting from the mixing tank, the pulp suspension recirculates in the line through a pump and a head tank to a channel where a measurement is made. The average flow speed, V_m, is set with manual valve by observing a magnetic flowmeter.

The fluid level in the head tank is fed back to the frequency inverter controlling the number of revolutions of the pump for a stable flow rate. The pulsation from the pump is absorbed by the tank. The channel is 2 m long, and a rectangular section 100 mm high and 5–20 mm wide is made of transparent material. The section facilitates the measurement of consistency unevenness with turbulence generators having various shapes and dimensions.

Coordinates are X in the flow direction, Y in the width direction, and Z in the height direction, with $X = 0$ at the incoming end. Consistency unevenness is defined as the change of fiber density averaged in the Y direction as measured by light intensity through a small area (0.4 mm × 0.4 mm) of the flowing pulp suspension, with the devices shown in **Figs. 3 and 4.**

The light intensity is closely related to the fiber density,[2] w, where w is obtained by multiplying the local fiber density ρ_s by the fluid width b:

$$w = \rho_s b \qquad (1)$$

The standard deviation σ_w calculated from these w values is used to compare consistency unevenness and is under-

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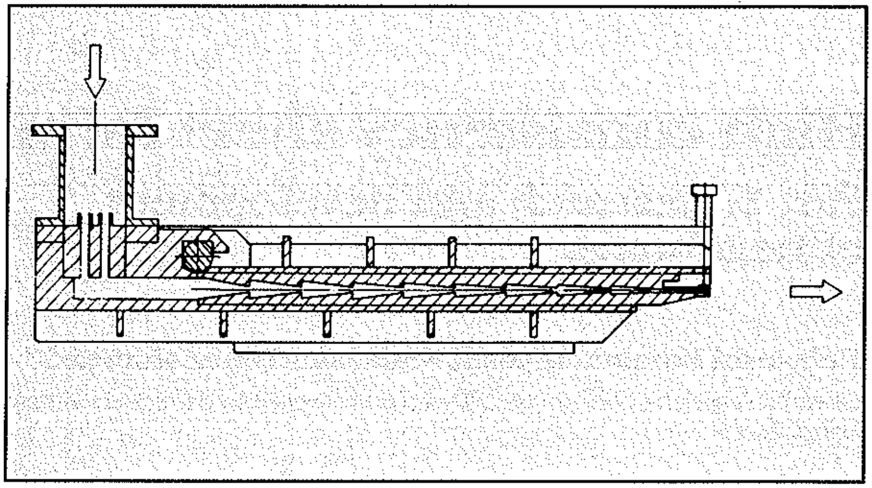
[1]Sugawara, H., Wada, K., Shimizu, T., and Nomura, T., Japan Tappi J. 42(4) (1988).

[2]Takeuchi, N., Appita 37(3) (1983).

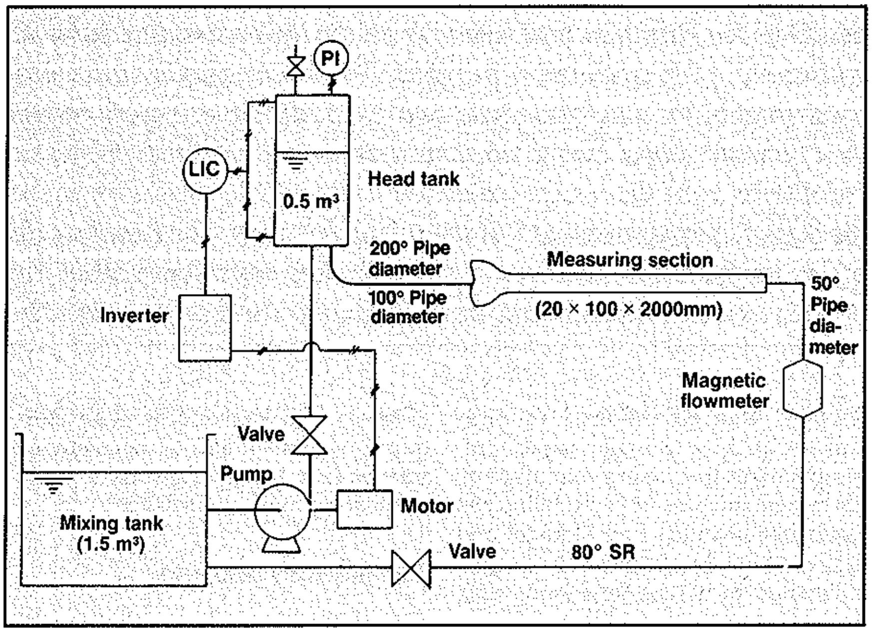
stood to be a representative value of the nonuniformity of fiber density.

A hardwood bleached kraft pulp of 3% consistency was used. (The freeness was about 400 mL CSF.) The fiber density meter is traversable along the X axis to observe various fluid channels at various locations. The frequency analysis of the unevenness of fiber density with respect to elapsed time at certain spots of X in combination with the average flow speed gives the distribution of floc diameters.

1. Headbox of the saw-blade type



2. The elementary experimental device



Fiber dispersion by the hydraulic turbulence

Figure 5 illustrates how the consistency unevenness changes as the pulp is agitated by turbulence generators of various types, with the average speed kept at 8 m/s and the position of X equal to 1 m and greater. In a straight duct without any turbulence generators, dispersion does not occur, and the consistency unevenness remains constant. A sharply narrowing duct shows remarkable reduction of consistency unevenness at the stepping region and approaches a level close to that of the straight channel. With the combination of sharp expansion and gradual contraction, called the "saw-blade," the greatest fiber dispersion is obtained, and its consistency unevenness stays low even after the turbulence zone.

Figure 6 shows more specifics with a close-up of the saw-blade zone. Repeated expansion and contraction, especially at an average speed of 2 m/s, results in excellent dispersion. The reflocculation at the final stage is low.

Model of dispersion

A model is proposed to express the process of hydraulic turbulence as it is generated and as it decays in a flow passage, dispersing fibers and allowing reflocculation with changes in consistency unevenness. **Figure 7** illustrates this process.

The turbulent flow forms and destroys the flocs, causing consistency unevenness in the flow. The transition of the consistency unevenness downstream of the turbulence generator is supposed to be the process of recovering equilibrium between the flow speed unevenness and the consistency unevenness. If the final consistency unevenness is the equilibrium of this process, the most important factor in the design of the flow channel will be how to generate turbulence and how to dampen it.

The dispersing ability is calculated by the following formulae:

$$D_1 = (\sigma_{w1} - \sigma_{w2})/\sigma_{w1} \quad (2)$$

$$F = (\sigma_{w3} - \sigma_{w2})/\sigma_{w3} \quad (3)$$

$$D_2 = (\sigma_{w1} - \sigma_{w3})/\sigma_{w1} = (D_1 - F)/(1 - F) \quad (4)$$

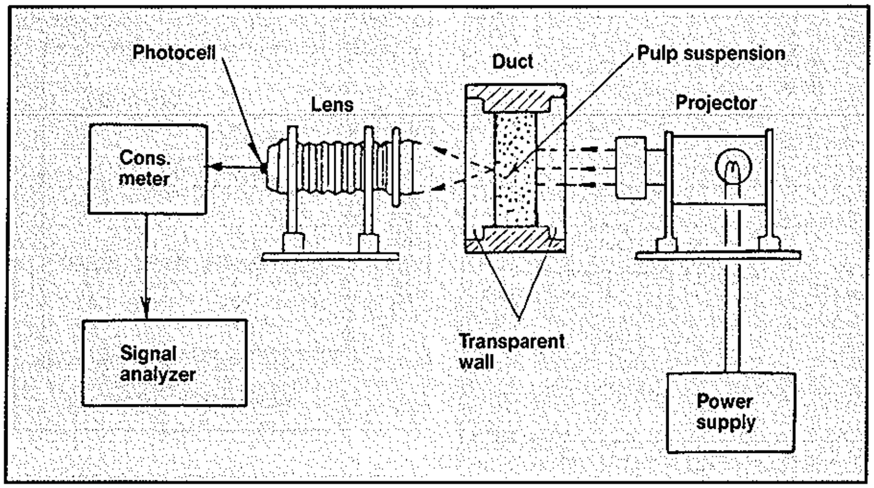
where

D_1 = initial dispersion close to the turbulence generator
σ_w = consistency unevenness
F = the rate of reflocculation
D_2 = the total dispersion rate.

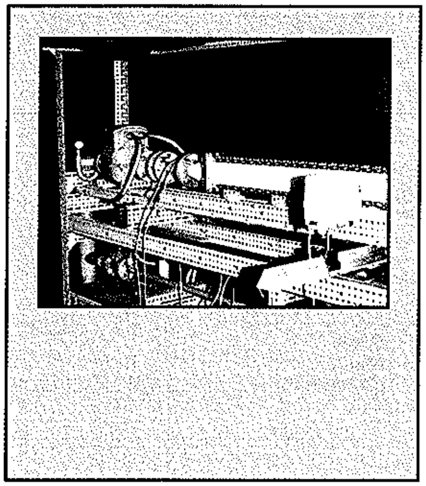
It is important for a headbox to have as large a D_2 as possible. In other words, it should have a large initial dispersion, D_1, and a small rate of reflocculation, F. (Reflocculation starts to take place soon after the initial dispersion.)

Figure 8 shows a plot of D_1 vs. mean velocity. The smaller the gap and the more gaps there are, the higher is the initial dispersion. However, D_1 seems to be saturated at around 4 m/s. The saw-blade has the highest initial dispersion.

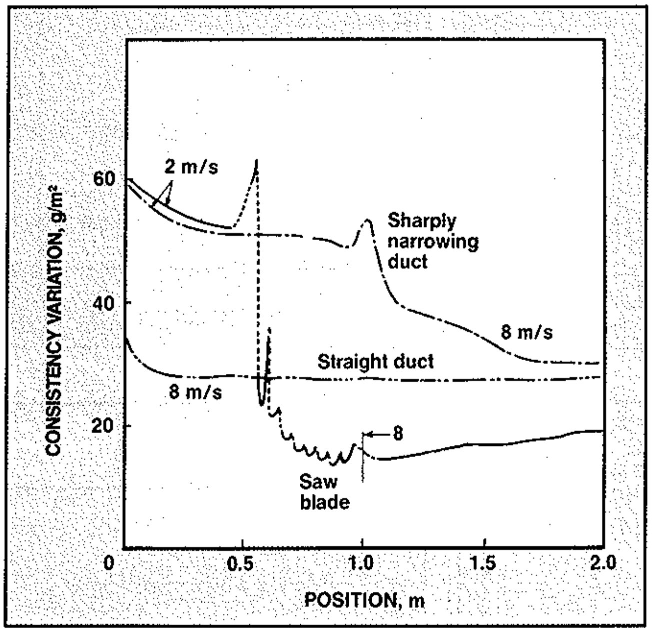
3. The setup for measuring fiber consistency unevenness



4. Photograph of duct model



5. Fiber dispersion for various duct models



6. Fiber dispersion for saw-blade type duct

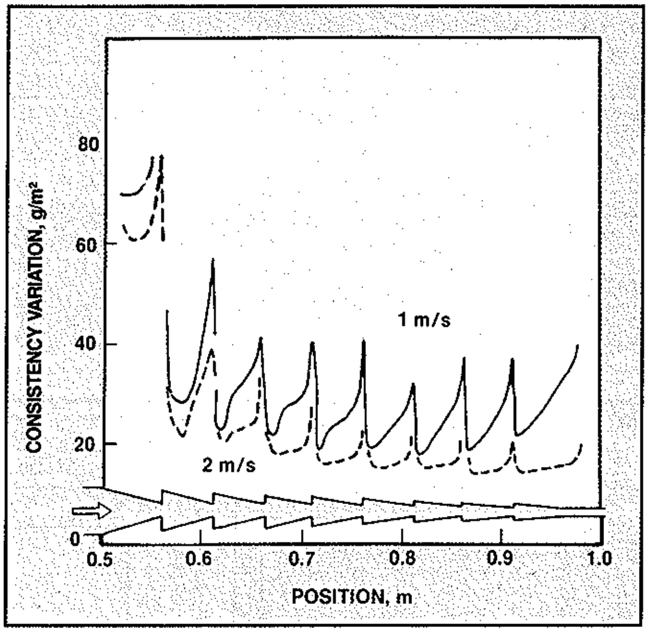


Figure 9 shows the relationship of reflocculation rate F to mean velocity. More orifices create higher initial dispersion rates and higher reflocculation rates at the same time. On the other hand, the reflocculation rate of the saw-blade is high at a low flow speed but low at a high flow speed.

Figure 10 shows the relationship between dispersion rate D_2 and velocity. As in Figs. 8 and 9, the saw-blade has a higher D_2 at higher speed, which suggests the possibility that it would be a good component in a headbox, with excellent fiber dispersion.

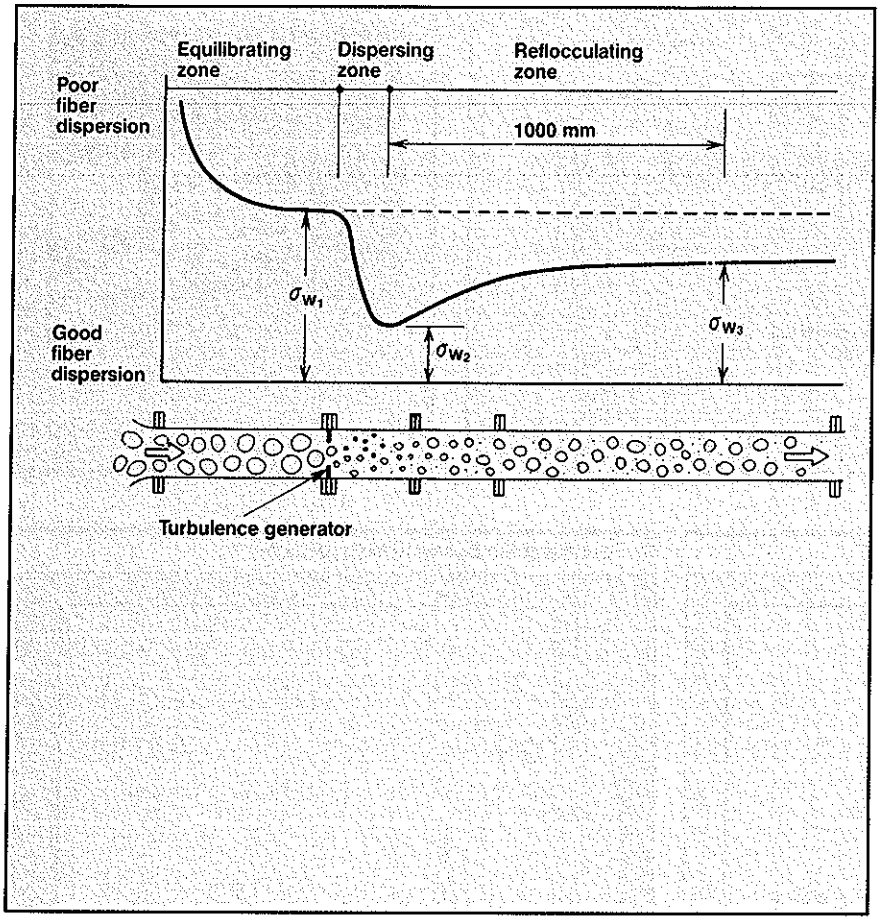
In addition, measurements of consistency unevenness in the expansion and contraction flow show that the sharp expansion region contributes much to the excellent fiber dispersion and that the gradual contraction region shows less reflocculation. Noncontact and simultaneous measurement by a Laser-Doppler Anemometer confirmed that the stronger the turbulence, the smaller the consistency unevenness, as shown in **Fig. 11**. This simultaneous measurement was made in the neighborhood of the wall in contact with the suspension.

Saw-blade turbulence generators

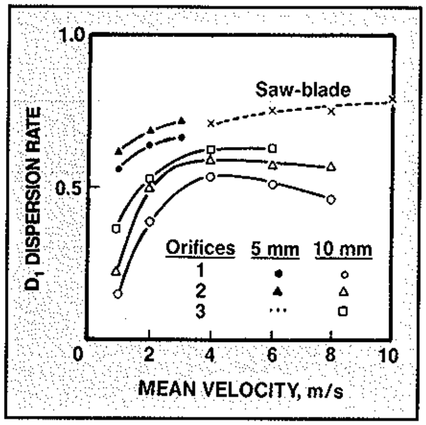
The saw-blade flow channel gives strong turbulence in the upstream area for minimizing consistency unevenness. In the downstream area, it gives small and gentle turbulence for minimizing reflocculation. Unevenness changes along the line of flow, and the shape of the flow channel should be designed with the line of flow in mind.

The original saw-blade channel was formed by combining straight surfaces with areas of sharp expansion and gradual contraction. **Figure 12** shows new shapes that have curved surfaces to check the unevenness of consistency. Each channel consists of three units in series of the same shape, with each unit composed of a "cup" and a "horn." In the "cup," the rate of change

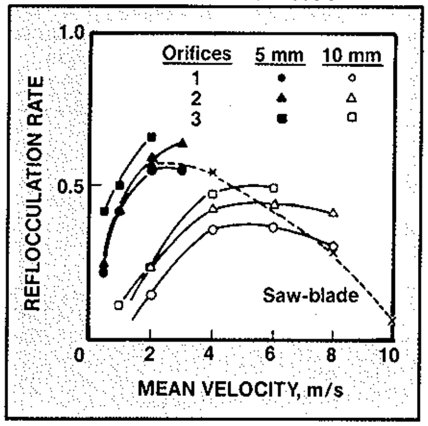
7. Fiber dispersion model



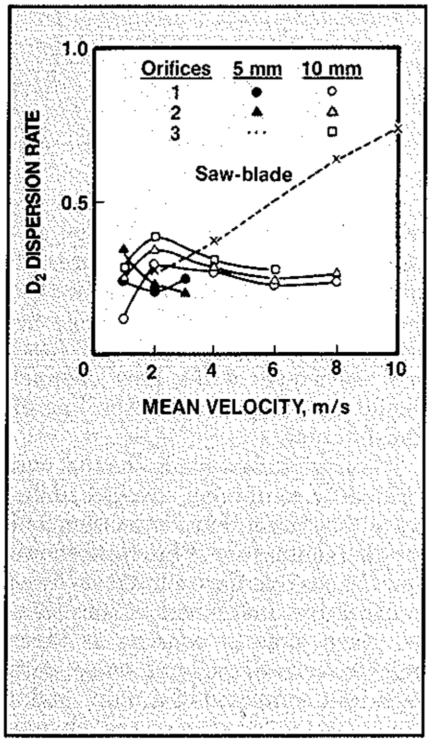
8. Dispersion rate D_1 of duct models



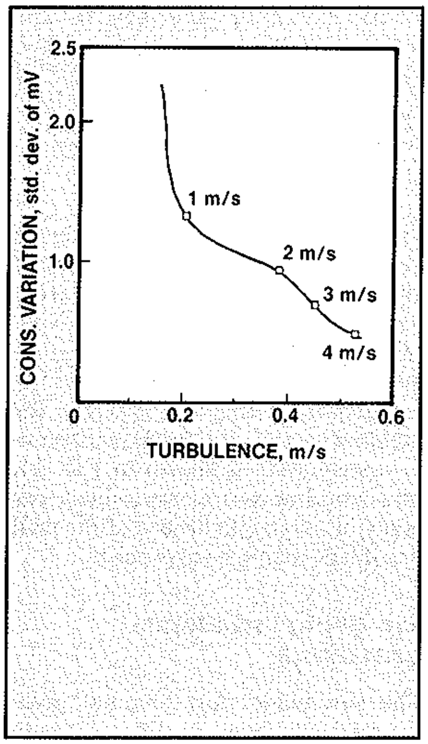
9. Reflocculation rate of duct models



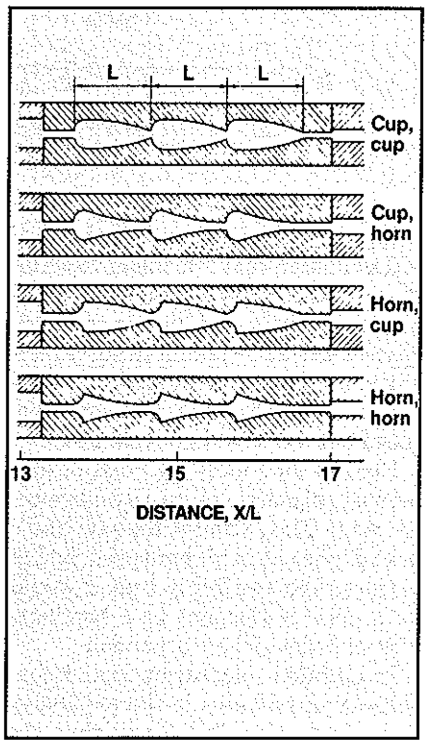
10. Dispersion rate, D_2, of duct models



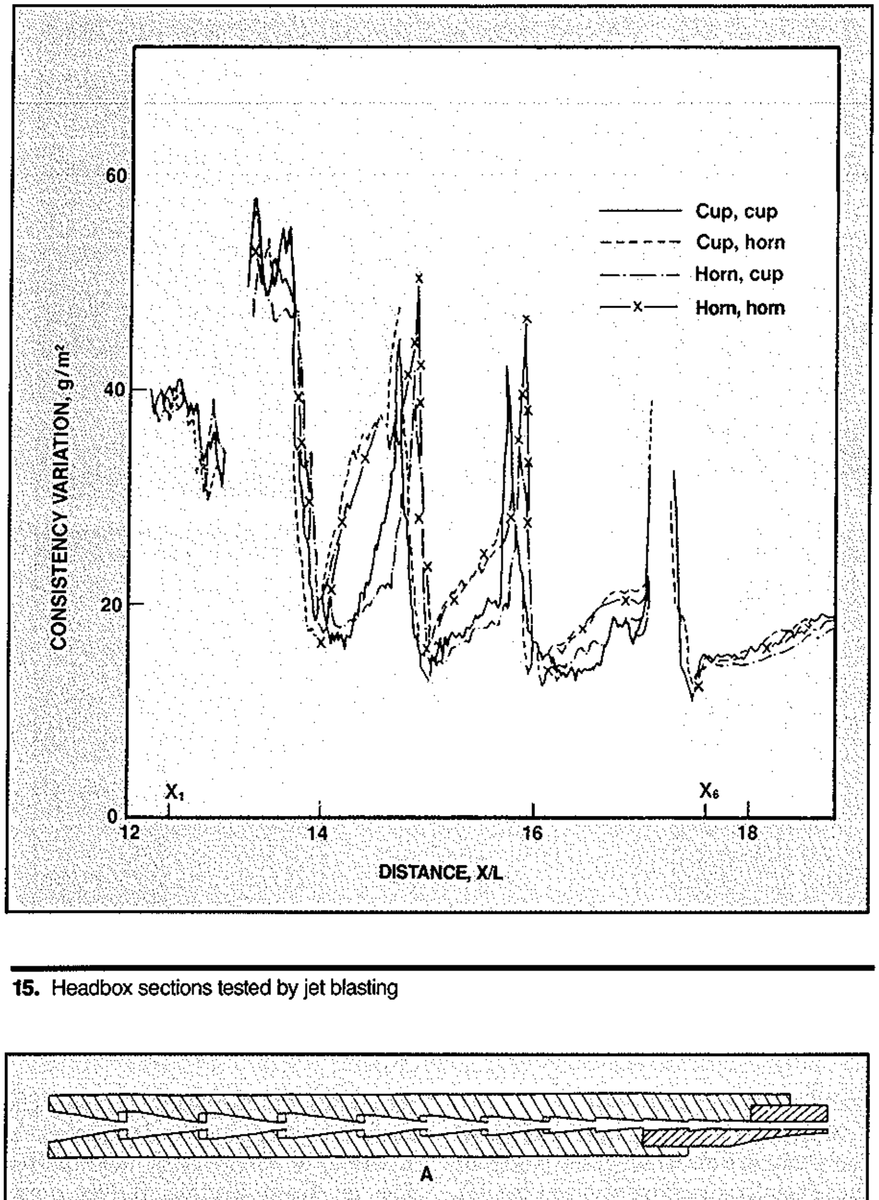
11. Consistency unevenness vs. turbulence intensity as measured by a Laser-Doppler Anemometer (1% consistency, $X = 1200$ mm)



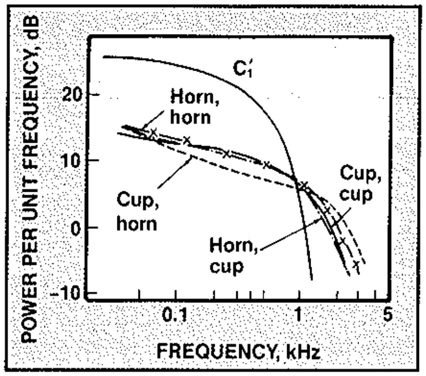
12. Combination of curved surfaces



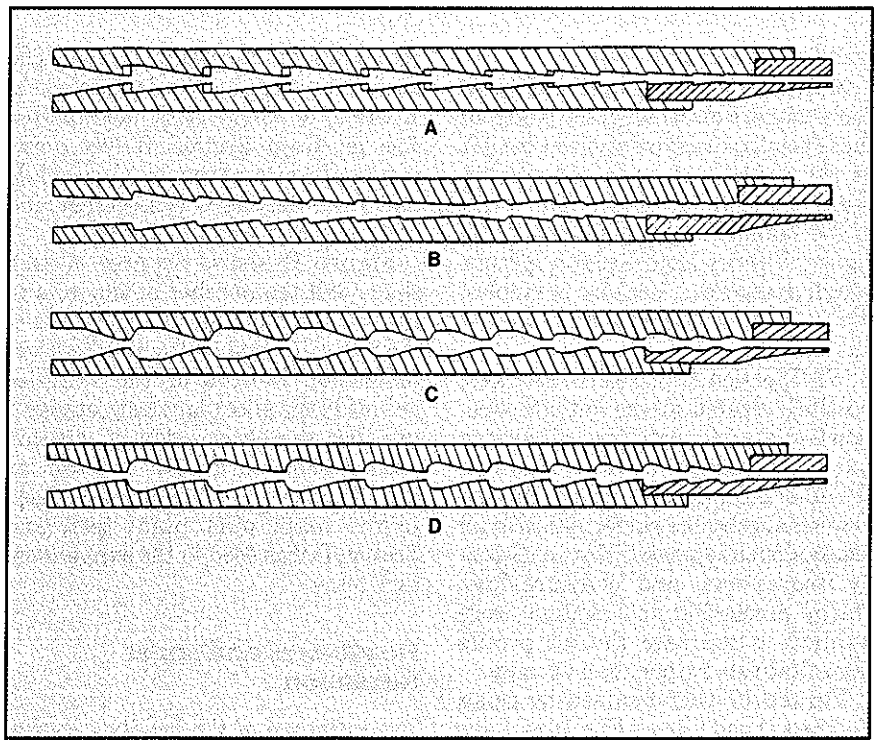
13. Fiber dispersion for improved saw-blade type duct models (3% consistency, speed = 8 m/s)



14. Frequency analysis of consistency signals (flow rate = 600 m/min)



15. Headbox sections tested by jet blasting



of the derivative of the channel profile curve (in the Y direction) is negative with respect to the channel length. In a "horn," the rate is positive.

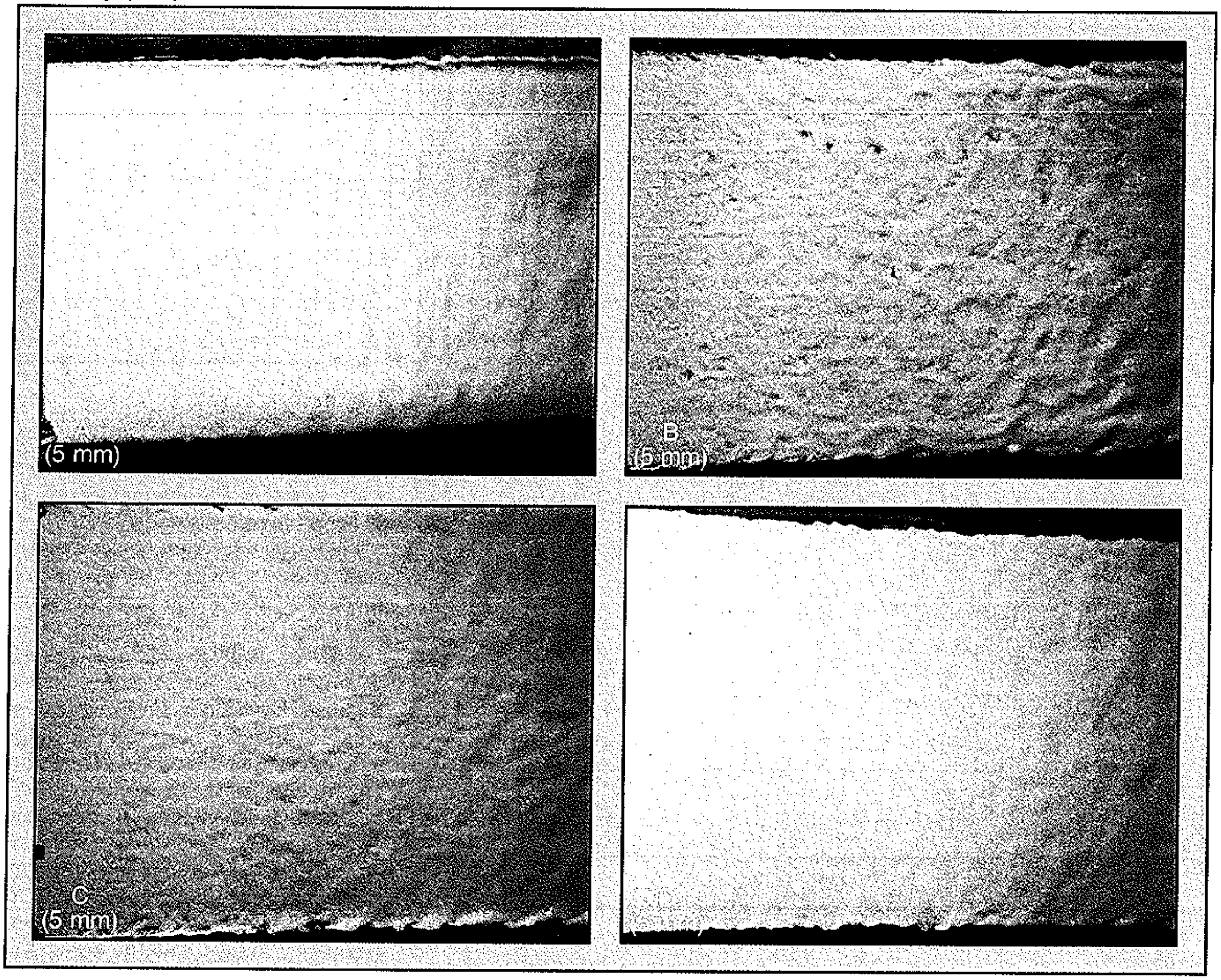
The measured consistency unevenness is shown in **Fig. 13.** The x axis is the distance in the flow direction. The y axis is the changing span of the signal for consistency unevenness. Where the span is higher, unevenness is larger. Each shape gives a different tendency in rate changes. A cup in the expanding flow increases dispersion, and a cup in the contracting flow means a slower increase in consistency unevenness.

Not much difference is noticed in the consistency unevenness at the downstream end of the flow, but frequency analyses of the signals at Positions X_1 and X_6 reveal some differences, as shown in **Fig. 14.** In this figure, the y axis is the power per unit frequency of the consistency unevenness signals. The higher the power per frequency, the more uneven the consistency.

The x axis is the frequency whose reciprocal corresponds to the size of the flocs when multiplied by the average flow speed. A higher frequency, then, means a smaller floc size. The signal strength at the upstream end is common (C_1'). At the X_1 position downstream, the progress of dispersion lowered the overall level; large flocs were destroyed, and small flocs were dominant.

The cup-horn shape especially indicates the tendency toward a reduced low frequency component and an increased high frequency component—that is, flocs are created that are more uniform and that are well dispersed. Thus, we expected that a headbox with improved shapes of flow

16. Photograph of jets from the headboxes



channel would be possible.

Jet of suspension from the headbox

Figure 15 shows the sections of the schematic diagram of the main headboxes on which we conducted preliminary jet tests. These sections were designed based on the findings during the elementary analysis and before mounting on the pilot plant for high-consistency sheet forming tests.

Each has a 350-mm slice width, and saw-blade turbulence generators follow the initial dispersing unit. Section A has regular saw-blades with ordinary cut-offs at its expanded areas. Section B has saw-blades in the upstream areas followed by a series of units having gradual expansion and sharp contraction. Section C has long expanded area after sharp expansion. Section D has the optimized curved walls of the cup-horn type.

Strobe-light photographs in **Fig. 16** show the vertical views of the jets from these headboxes, flowing from the left at 3% consistency, with a 3-mm lip opening and at 600 m/min. The width of the channel is also indicated in the figure. The jet from Section B looks rough and porous, because of ripples, while those of Sections A, C, and D are smooth.

With Section A, there are firm flocs, possibly created at the cut-offs. Section C offers adequate fiber dispersion but needs higher pressure loss than the others. On the other hand, Section D gives acceptable performance in all aspects, such as jet stability, consistency unevenness, and pressure loss. Image processing and analysis were applied to evaluate the jet profile quantitatively rather than visually.

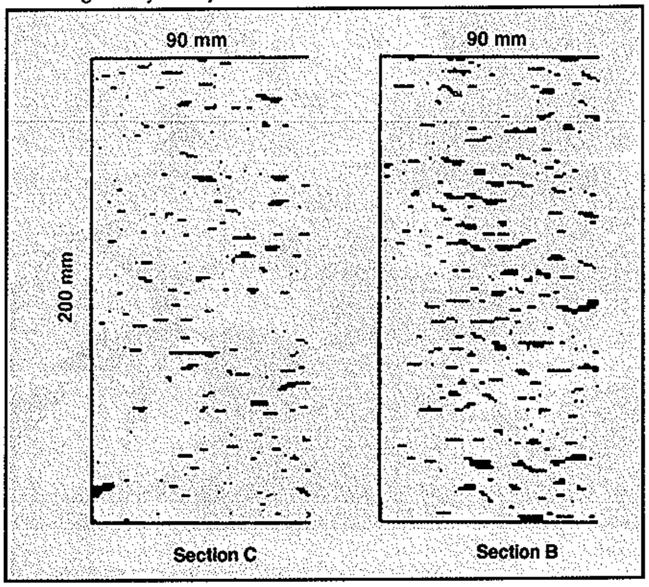
Figure 17 was obtained by using Sections B and C from Fig. 16 as video signal input to an image analyzer. The shade of waves on the jet surface is stressed by brightness modulation. The jet from Section B has many shades of waves of various sizes, while that from Section C is smoother and has fewer and smaller shades.

Figure 18 shows the area of each shade and the number of shadows in Fig. 17. Such quantitative analysis of the jets coincided well with the sheet formation indices of the samples gained in the pilot plant tests, suggesting that the observation of jets can predict sheet formation to some extent. The Section C headbox was used in the main pilot plant test, and Section D was used in the supplementary tests.

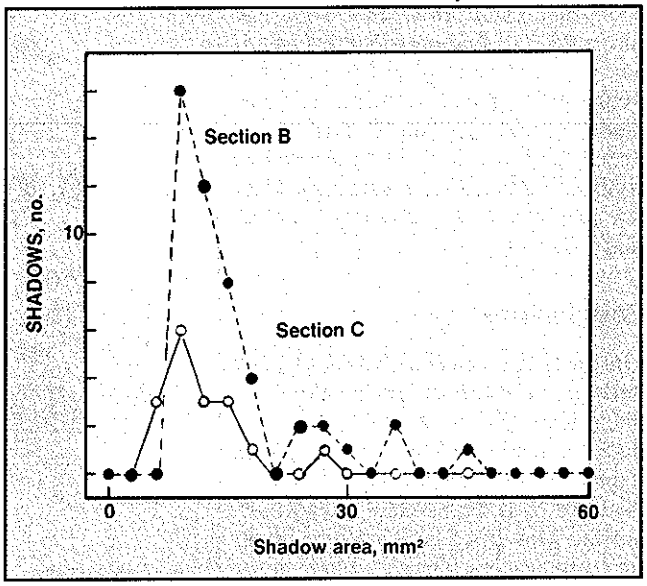
Headboxes and sheet formation

The influence of the headbox config-

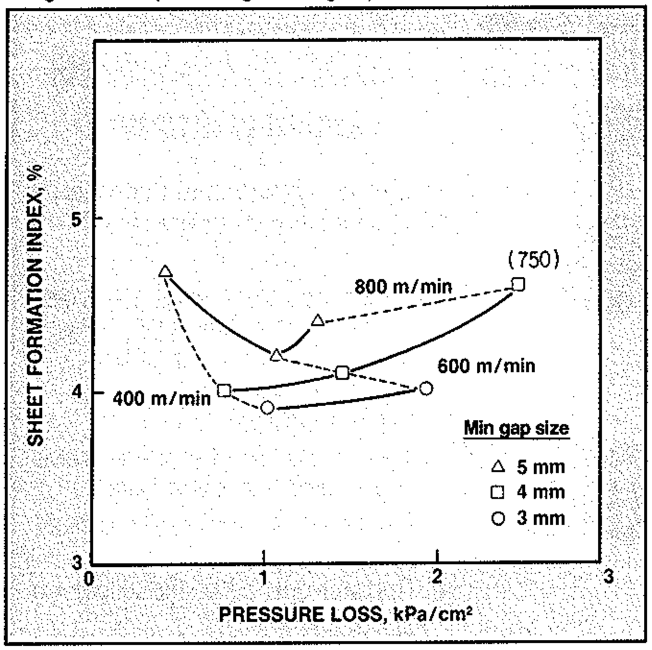
17. Image analysis of jets from Sections B and C



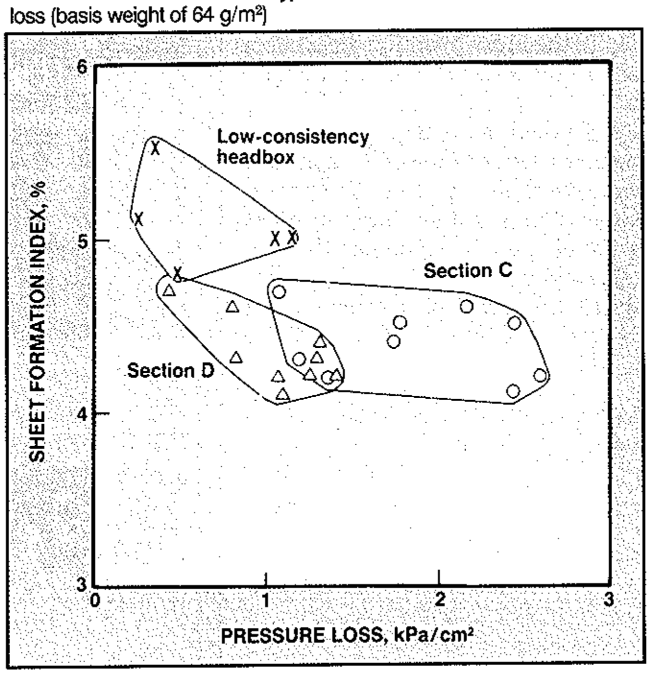
18. The area and the number of shadows of each jet



19. The influence of speed on sheet formation index and pressure loss using Section D (basis weight of 64 g/m²)



20. The influence of headbox type on sheet formation index and pressure loss (basis weight of 64 g/m²)



urations and pressure losses on sheet formation was studied in the papermaking tests in the pilot plant. **Figure 19** shows the sheet formation index and the pressure loss in Section D. The sheet formation index is a rate of floc intensity measured by a commercial formation tester for flocs of 0.5-12.5 mm in diameter.

The channel width was changed at operating speeds of 400-800 m/min. By reducing the width from 5 mm to 3 mm, the pressure loss was increased even at the same speed, and the sheet formation index was improved to below that obtainable at 600 m/min. Sheet formation tends to be best at a pressure loss of around 1 kPa/cm².

Such phenomena can be explained by the assumption that the jet is stabilized when the pressure loss is small and turbulence is weak but the floc dispersion is insufficient. In this case, the sheet formation becomes poor. On the other hand, higher pressure loss generates strong turbulence which brings better fiber dispersion but at the same time an unstable jet, which yields poor sheet formation. When the dispersion and stability are in a good balance, the sheet formation is the best.

Figure 20 shows the relationship between the sheet formation indices and the pressure losses of each headbox. Points are of similar speed and basis weight, with 0.6-3% headbox consistency for Sections C and D and for a hydraulic headbox designed for low consistency. This low-consistency headbox needs a small pressure loss, but the sheet formation index is high, meaning that formation is poor. This poor formation indicates that the conventional low-consistency headboxes are not applicable to high-consistency sheet forming without modification. Section C has a low formation index, but the pressure loss is high. Section D has comparatively low pressure loss and a good formation index.

Conclusions

The Section D headbox was developed with the intention of having excellent dispersion and a stable jet. It produced a good sheet on the pilot plant. Further development to a wider headbox will be needed to commercialize the high-consistency sheet forming process. The saw-blade headbox will be advantageous in that the multiple stages of the saw-blade will unify the pressure losses at each stage, resulting in uniform volume distribution in the cross-machine direction as long as the channel is made accurately.

A gradual increment of papermaking consistency followed by a gradual improvement in sheet formation, rather than a sudden jump up to 3%, is anticipated by applying the idea, achievements, and know-how accumulated through this development to the design of conventional headboxes as well.

Received for review March 4, 1988.
Accepted June 13, 1988.