Fiber flocculation in pulp suspension flow

Part 2: Experimental results

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ABSTRACT *The purpose was to quantify the primary effects and the interaction effects of selected factors on floc size distribution and, hence, on the uniformity of fiber dispersion. Factors studied include consistency, velocity in turbulent flow, temperature, and fiber surface characteristics. Fiber dispersion is enhanced as consistency, fiber length, and temperature are decreased, with the first two variables being dominant. Velocity has a complex influence, but flocculation is generally minimized by increasing velocity in turbulent flow. Electrostatic field effects have a strong influence on the floc size distribution. These results are based on coupling the theoretical model of Part 1 with experiments using digital signal analysis of light transmission through flowing pulp.*

KEYWORDS
Analysis
Electrostatics
Flocculation
Mathematical models
Pulping
Simulation

Packaging and the carrying of information are important uses of paper. In the carrying of information, the uniformity of optical properties such as opacity, brightness, gloss, and shade of color is paramount. In the packaging, the uniformity of the mechanical properties such as tensile strength, compressive strength, tear strength, and folding endurance is paramount. These properties and the properties of basis weight, thickness, porosity, permeability to gases and liquids, and ink absorption, are affected by the extent of fiber dispersion in the paper—or "formation," which depends on the floc size distribution in that paper. The effects on flocculation of the four variables believed to be most critical are examined here: velocity, temperature, consistency, and fiber species. Hardwood and softwood fibers were used to characterize the last variable, and fiber length was chosen as the overall index of the combined characteristics of fibers such as modulus, slenderness ratio, flexibility, and others which influence the tendency to floc (*1-4*).

The experiments were based on real-time signal analysis using a digitized representation of light transmission waveforms. A flow loop built with a Plexiglass test section, as shown in **Fig. 1**, was used to receive the transmitted light through the flowing pulp. This signal, when digitized, has a resolution of 0.3 mm, and it is directly analyzed through a microcomputer. Ninety waveforms were collected for each condition, and each waveform represents the equivalent of 30 cm (12 in.) of sample in the direction of the flowing pulp. The floc size distributions that were generated provide the necessary experimental input to fit the parameters for the theoretical model developed in Part 1 (*5*).

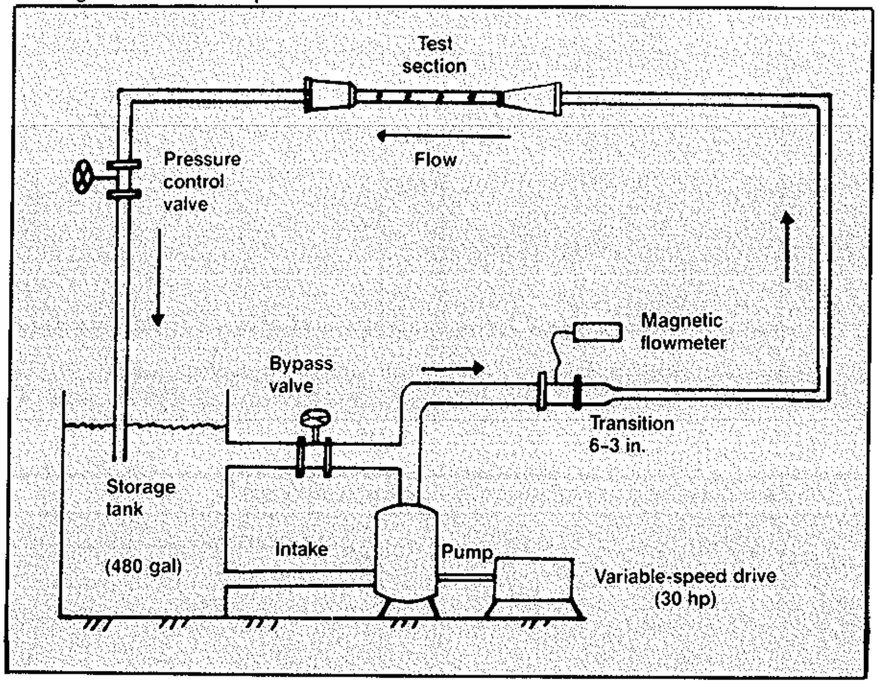
Results

A two-level factorial design (*6*) can be used for experiments with variables of discrete steps, such as chemical additives, consistency, and fiber length, and for continuous variables such as velocity and temperature. The two levels are coded "H" for the high value of Variable Y, and "L" for its low value. The high and low levels are far enough apart so that the effect of Variable Y is larger than the experimental error. For an experimental design with four independent variables, 2^4 or 16 different experiments are conducted to obtain the desired set of primary and interaction effects. These effects were determined at Position 1 of the test section.

Table I presents the experimental design pattern and the associated experimental mean floc size, F, standard deviation, σ, and total number of flocs of the distributions. An important trend derived from the table is that the mean floc size is approximately equal to the standard deviation. That type of distribution is called a "negative exponential distribution."

The model derived from the factorial design yields the equations relating dependent and independent variables. These equations, derived in the

1. Diagram of the flow loop



I. Two-level factorial design

Trial	Y_1	Y_2	Y_3	Y_4	F, mm	σ, mm	Total number of flocs
1	L	L	L	L	1.47	1.20	7333
2	H	L	L	L	1.53	1.35	9251
3	L	H	L	L	1.59	1.56	6796
4	H	H	L	L	1.59	1.44	8822
5	L	L	H	L	1.77	1.92	8376
6	H	L	H	L	1.80	1.56	7819
7	L	H	H	L	2.13	2.13	7275
8	H	H	H	L	2.04	1.71	7275
9	L	L	L	H	2.49	2.40	3683
10	H	L	L	H	1.71	1.53	5327
11	L	H	L	H	2.22	2.52	3923
12	H	H	L	H	1.86	1.86	4800
13	L	L	H	H	4.41	5.07	3624
14	H	L	H	H	2.64	2.49	5879
15	L	H	H	H	4.47	5.52	3754
16	H	H	H	H	2.97	3.00	5361

Y_1 is velocity, where H = 3000 ft/min and L = 300 ft/min.
Y_2 is temperature, where H = 75°C and L = 25°C.
Y_3 is consistency, where H = 1.35% and L = 0.5%.
Y_4 is fiber length, where H = softwood (~4 mm) and L = hardwood (~1 mm).

appendix, quantify the primary effects and the interaction effects of all the variables on floc size distribution. These effects are summarized in **Table II**, where the relative influence of each variable or of the interaction of variables on the floc size distribution is related to the total number of signs ("+" or "–") given to each effect, where "+" and "–" signify an increase or a decrease in flocculation, respectively.

Consistency and fiber length have the most dominant primary effects on the floc size distribution, with a significant interaction effect among themselves and velocity (**Figs. 2 and 3**). Velocity has a mixed effect. Although its primary effect is sizable, it is coupled with a strong interaction with consistency and fiber length. This coupling makes the velocity effect more influential in conjunction with both higher consistency and longer fibers. The velocity effect on hardwood fiber flocculation at 0.5% consistency was unexpected, because flocculation increased slightly with increasing velocity. That effect was reversed at 1.35% consistency, showing that the velocity effect is complex as a result of the different mechanisms that it can enhance. Vortices might favor flocculation, and shear might break flocs. These two mechanisms are dependent on consistency and fiber structure, which explains the strong interaction effect that velocity has with these two variables.

Temperature showed a less dominant effect on flocculation than the other variables. Higher temperatures enhanced flocculation. This finding suggests that if flocculation is a severe problem, wet ends should be operated at the lowest temperature possible, even though this conflicts with the common papermaking practice of heating the stock to improve drainage.

The total number of flocs detected during the experiments were computed, and the analysis showed that hardwood had more than three times the number of flocs than softwood, with lower mean floc size at fixed conditions. Consistency had a minor effect on the number of flocs for both hardwood and softwood. This finding suggests additional fibers entanglement in established networks of fibers. Temperature had a pronounced effect on the number of flocs. The effect of temperature must be complex because it effects fiber modulus (and hence network strength), the kinematic viscosity of water (and hence turbulence and shear stress), and surface characteristics of fibers. The net effect of increasing temperature was to decrease the overall number of flocs and increase floc size, suggesting that temperature enhanced floc-floc collision and entanglement.

Another significant aspect of this study is the predictive capability of Eqs. 1 and 2 in the appendix for conditions different from those of the experiments. To analyze the accuracy of that prediction, the floc size distribution of a bleached pulp of 80% hardwood and 20% softwood was determined experimentally at a consistency of 1.25%, a temperature of 25°C, and a velocity of 100 m/min (300 ft/min). **Table III** shows the results obtained experimentally and from the equations. The comparison suggests that this analysis can accurately predict flocculation over a wide range of conditions with a minimum number of experiments.

Conclusions

This experimental method to study flocculation in turbulent suspension flow, coupled with the theoretical model, can now quantify floc size distribution. It can accurately predict flocculation because it not only quantifies the primary impact of each variable but also takes into account the interactions among variables.

Because the essential elements of this analysis include the fixed geometry of the test section, one can apply this technique to either a laboratory closed-loop system or to a straight-through flow stream directly from the paper machine. Used with the straight-through stream, the analysis allows us to directly evaluate dispersion on the paper machines, including the diagnosis of formation stabilization. The results of this study are consistent with practical papermaking experience, in which hardwood is superior to softwood in providing a more uniform sheet and consistency is known to have an enormous effect on flocculation.

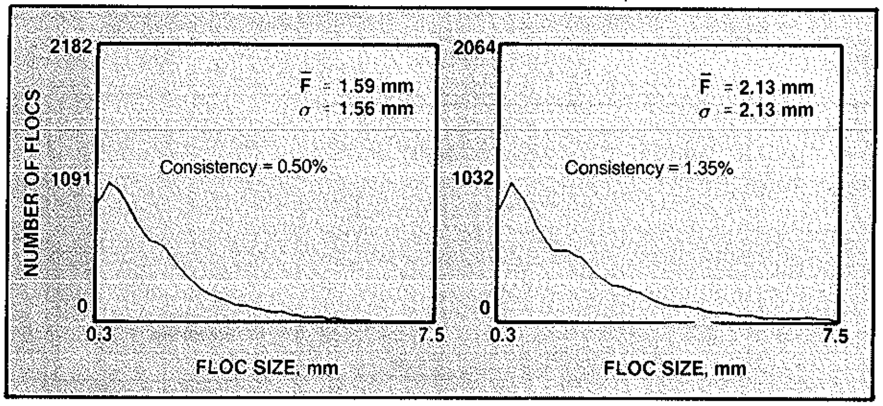
Experimental techniques

In the flow loop, fiber optic cables are attached to each side of the test section at four different locations. Light from a source on the bottom side of the test section is transmitted through the pulp and is received on the top side. A photodiode converts that signal to an analog voltage which, in turn, is digitized. The programmable digitizer is interfaced with the microcomputer for immediate analysis of the data. The sampling rate of the digitizer is adjustable so that the resolution of the waveforms is kept constant (0.3 mm) at different velocities.

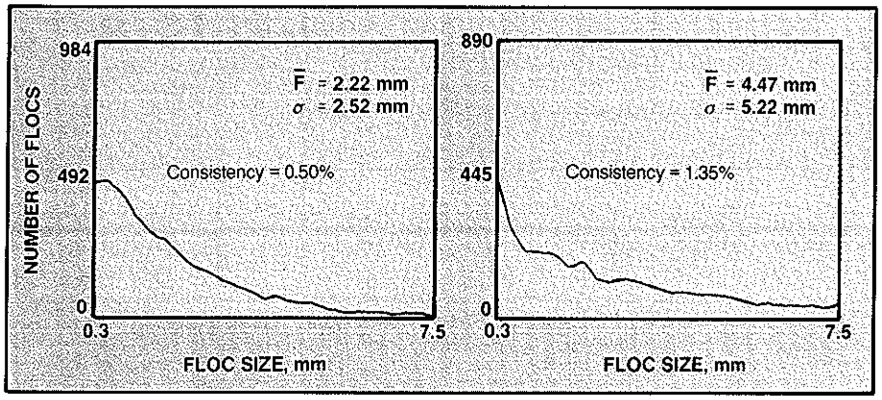
Since the waveforms represent transmission vs. time, the flocs are represented by waveform minima. Flocs are therefore defined as zero-crossings of the waveform with respect to the average value, and they are bounded by these intersections. The time domain is converted to a size domain using both the flow velocity and the sampling rate on the digitizer.

Ninety waveforms are collected for each condition, generating an appropriate statistical distribution of floc size. The smallest floc size measured is 0.3 mm, and all other sizes are multiples of that fraction (0.6 mm, 0.9 mm, 1.2 mm, . . .).

2. The effect of consistency on hardwood fiber flocculation at low speed



3. The effect of consistency on softwood fiber flocculation at low speed



II. Primary and interaction effects on flocculation

	Velocity	*Temperature*	*Consistency*	*Fiber length*
Velocity	---	+	---	---
Temperature	+	++	+	+
Consistency	---	+	++++	+++
Fiber length	---	+	+++	++++

III. Floc size distribution of 80% hardwood, 20% softwood pulp at 1.25% consistency, 25° C, 300 ft/min

	F, mm	*σ, mm*	*No. of flocs*
Experiments	2.22	2.28	6854
Eqs. 1 and 2	2.25	2.40	7290

*These fall within trial Nos. 5 and 13 of Table I, as expected.

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Appendix

The model derived from the two-level factorial design yields the equations that relate dependent and independent variables. Solving for the mean floc size (in millimeters) yields Eq. 1:

$$\bar{F} + 2.28 - 0.28\,Y_1 + 0.065\,Y_2 + 0.48\,Y_3 + 0.56\,Y_4 + 0.030\,Y_1Y_2 - 0.14\,Y_1Y_3 - 0.28\,Y_1Y_4 + 0.060\,Y_2Y_3 - 0.030\,Y_2Y_4 + 0.29\,Y_3Y_4 - 0.12\,Y_1Y_3Y_4 \quad (1)$$

Solving for the standard deviation (in millimeters) yields Eq. 2:

$$\sigma = 2.31 - 0.44\,Y_1 + 0.12\,Y_2 + 0.58\,Y_3 + 0.70\,Y_4 + 0.015\,Y_1Y_2 - 0.26\,Y_1Y_3 - 0.35\,Y_1Y_4 + 0.010\,Y_2Y_3 + 0.020\,Y_2Y_4 + 0.36\,Y_3Y_4 - 0.17\,Y_1Y_3Y_4 \quad (2)$$

Solving for the total number of flocs N yields Eq. 3:

$$N = 6206 + 610\,Y_1 - 205\,Y_2 - 36\,Y_3 - 1662\,Y_4 - 47\,Y_1Y_2 - 198\,Y_1Y_3 + 187\,Y_1Y_4 - 174\,Y_2Y_3 + 121\,Y_2Y_4 + 146\,Y_3Y_4 + 365\,Y_1Y_3Y_4 \quad (3)$$

In all three equations:

$$Y = [(\text{variable level}) - (H + L)/2]/[(H - L)/2] \quad (4)$$

The partial derivative

$$(\delta/\delta Y_i)_{Y_{j \neq i}}$$

can be used to determine the effect of each variable on the size distribution.

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