

A comparative study of two automated techniques for measuring fiber length

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FIBER LENGTH AND WIDTH ARE fundamental pulp properties that relate directly to paper properties. Reliable methods for measuring fiber dimensions are essential. The traditional method involves classifying the pulp into screened fractions (1) and then measuring the weight and length of fibers in each fraction to calculate the weighted average length by weight (2). A faster and less tedious approach is to use an automated optical analyzer (3), in particular the Kajaani unit. This instrument has been the subject of several studies (4–8) and is widely used in industry. More recently, improvements in computer-based image-processing systems have led to the development of other fiber analyzers that provide rapid and operator-independent measurements (9, 10).

This study compares the results obtained from two automated optical methods that operate on different measuring principles. The Kajaani FS-200 measures fiber length using an indirect method. The Galai CIS-100 uses a direct visual method. Reference measurements were obtained from microscopic image analysis.

The calculated results for both methods rely on the assumption of a linear relationship between fiber length and coarseness. This assumption is examined in a brief review of the meaning of average fiber length. Preliminary measurements of fiber length and coarseness in nonclassified and classified bleached kraft eucalypt pulp suggest that the rela-

tionship between fiber length and coarseness may not be linear.

OPERATING PRINCIPLES OF MEASUREMENT TECHNIQUES

Kajaani FS-200

The FS-200 unit (Kajaani Electronics Ltd.) is specifically designed to evaluate fiber-length distributions of cellulosic fibers. Measurements are based on the ability of these fibers to change the direction of polarized light. The FS-200 is used extensively in the pulp and paper industry because it is fast (typically, it can size 20,000 fibers in about 10 min) and simple to use. A detailed description of its operating principle can be found in the literature (4, 5).

Because the FS-200 operates using an indirect optical technique, it does not provide any indication about the way fibers are being counted and sized. For instance, if two fibers are stuck together as they enter the capillary tube, they will be counted as a single fiber. Moreover, if they do not enter perfectly straight, the measured projected length will be smaller than the real one.

Galai CIS-100

The CIS-100 system (Galai Production Ltd.) is a particle size analyzer based on the direct visualization of the fibers. Contrary to the FS-200, the CIS-100 is not restricted to cellulosic fibers and thus is more generally applicable. The CIS-100 incorporates, in a single unit, two different techniques to characterize particles: laser-based time-of-transition theory (9) and camera-based shape analysis (11). In this study, only the latter was

ABSTRACT

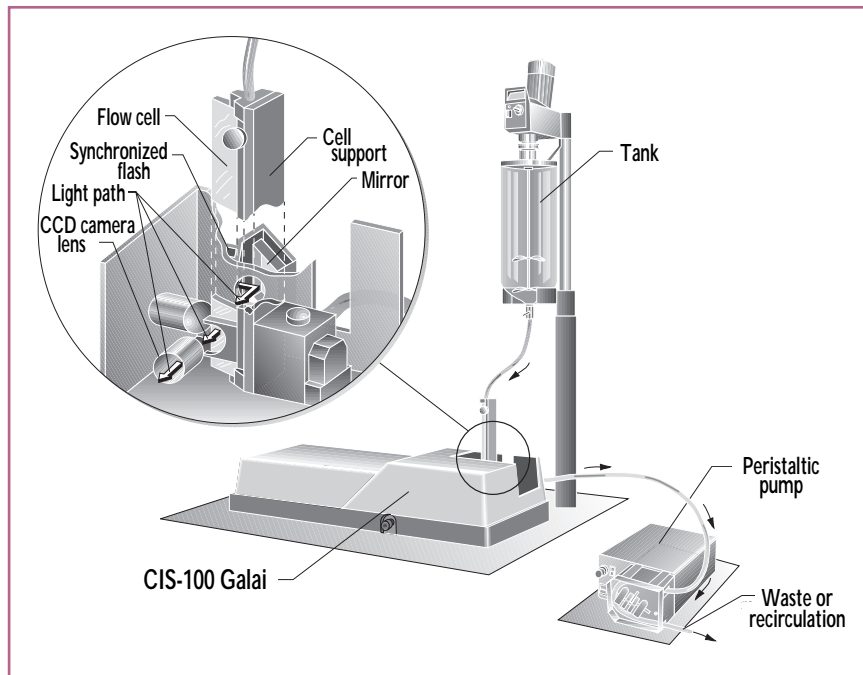
Measurements from two automated fiber analyzers—Kajaani FS-200 and Galai CIS-100—are compared. The FS-200 measures fiber length and coarseness via an indirect optical method. The CIS-100 measures fiber length and width by analyzing video images of fibers. Length-weighted average fiber lengths for the FS-200 were 10–20% lower than those for the CIS-100. Reference measurements from microscopic image analysis suggest that while the CIS-100 measures length more accurately than the FS-200, it is not accurate enough to measure the width of the thin eucalypt fibers used in this study. Both instruments showed good agreement between weight-weighted fiber length for the whole pulp and weight-weighted length calculated from fiber fractions classified in a Bauer–McNett device.

Application: Compares the performance of two automatic fiber analyzers, the Kajaani FS-200 and the Galai CIS-100.

used to assess fiber length distributions.

Figure 1 illustrates the CIS-100 unit. The fiber suspension is uniformly stirred in the tank and pumped through a rectangular-cross-section flow cell (GCM-104L), whose configuration tends to align the fibers along the flow direction. A synchronized pulsed flash illuminates the moving fibers, with strobing light adjustable to the video acquisition rate. A CCD video microscope captures the fiber dynamic images, which can be seen in a high-resolution monitor. These images are digitized by a host computer, and shape analysis proceeds via software loaded on the system.

Sample measurements are optimized through such features as rejection of out-of-focus particles and



1. Experimental setup for fiber measurement with the CIS-100

automatic lighting correction. Although the cell module is designed to orient the fibers, correct alignment is seldom achieved. Misalignment is taken into account by using image-analysis filters such as shape factor [$(4\pi \times \text{projected area})/\text{perimeter}^2$] and aspect ratio (minimum Feret diameter/maximum Feret diameter). For the present work, a preliminary study was undertaken to select the shape-filter values that would eliminate anomalies—particles other than fibers, touching or bending fibers, and fiber bundles—from the measurements.

Once the combination of analysis parameters had been selected, the image processing was automatically performed through a programmed routine that included segmentation by thresholding, object painting, geometric filtering, and statistics. The output parameters were the specific fiber length and width distributions, defined respectively as the length and width of a rectangle whose area and perimeter match those of the fiber image.

Microscopic imaging analysis

A computer-controlled microscopic image analysis was performed to

check the results of the CIS-100 system's automated image analysis. The equipment used for these measurements included an Olympus Microscope (BH-2) coupled to a CCD camera connected to a computer. The specific fiber length and width distributions were calculated with the Olympus software (CUE-2 version), which is the same as that used in the CIS-100 system (both supplied by Galai Production Ltd.). The microscopic image analysis also used shape filters to exclude curved and touching fibers. The main difference between the microscopic analysis and the CIS-100 imaging procedure is that the fibers can be visualized almost individually in the microscopic analysis (usually only one fiber per frame). Because of the higher magnification of the microscope assembly compared with that of the CIS-100 ($\approx 160X$ vs. $30X$ at the monitor), more accurate results are expected with the microscope technique. The main drawbacks are the reduced number of fibers sized (when compared with the automated techniques) and the more tedious and time-consuming procedure, which makes this technique

inadequate for routine purposes.

AVERAGE FIBER LENGTH

As in any other particle-size measurement, it is possible to calculate several kinds of average (or mean) fiber lengths (12), the most popular being the numerical, the length-weighted, and the weight-weighted (mass weighted) averages, defined as

$$L_n = \sum n_i l_i / \sum n_i \quad (1)$$

$$L_l = \sum n_i l_i^2 / \sum n_i l_i \quad (2)$$

$$L_w = \sum w_i l_i / \sum w_i \quad (3)$$

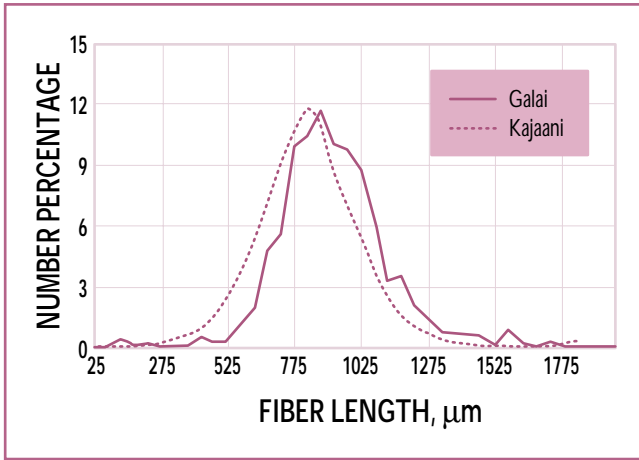
where

- L_n = numerical average length
- L_l = length-weighted average length
- L_w = weight-weighted average length
- n_i = number of fibers in the i th class
- l_i = mean length of the i th class
- w_i = weight (or mass) of fibers in the i th class.

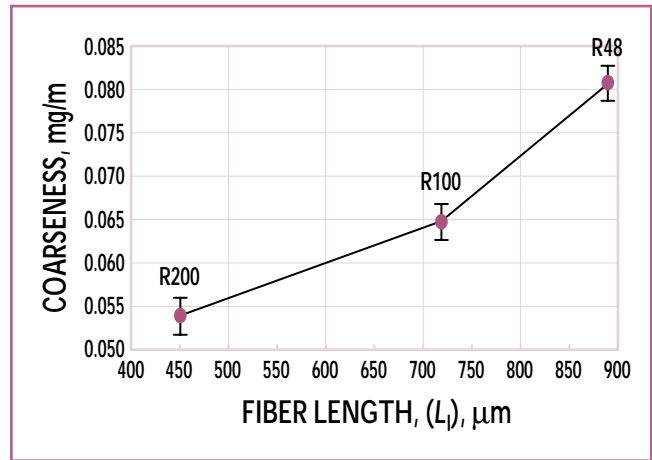
Since the techniques used in the present work count and distribute fibers according to length, the first two averages (Eqs. 1 and 2) are easily calculated. Equation 2 is used more often because it correlates better with paper properties and is not so dependent on the proportion of the fines (7, 13).

Problems arise, however, when a weight-weighted average length is required, since most methods of measuring fiber length do not discriminate fibers according to their weight (or mass). The conventional method is to use a classification method, such as the Bauer-McNett, to separate the pulp into fiber-length fractions and then to determine the weight and the average fiber length of each fraction. The weight-weighted average fiber length is then given by Eq. 4 (1).

$$L_w = (w_1 L_1 + w_2 L_2 + \dots + w_5 L_5) / W$$



2. Distribution of fiber length of R48 fraction as given by the FS-200 and the CIS-100



3. Coarseness vs. average length-weighted fiber length as given by the FS-200

(4) gives

where

W = total oven-dry sample weight added to the classifier.

The variables w_1, w_2, \dots, w_5 are the oven-dry weights of the five fractions (the fifth being the one lost through the finest screen), while L_1, L_2, \dots, L_5 are the corresponding average lengths. This is the same expression as Eq. 3 but with fewer size classes. The average length of each fraction can be determined using any of the aforementioned measuring methods.

Nevertheless, other calculation formulas that eliminate the classification process have been adopted to estimate weight-weighted average fiber length. For instance, if the fiber coarseness (defined as the mass of fibers per total length, $c = w/L$) is considered constant for all fibers, then Eq. 3 can be written as

$$L_w = \frac{\sum n_i c l_i^2}{\sum n_i c l_i} = \frac{\sum n_i l_i^2}{\sum n_i l_i} \quad (5)$$

Using this approach, the weight-weighted average coincides with the length-weighted average (Eq. 2). If, on the other hand [as is more reasonable (13)], the coarseness is proportional to fiber length ($c = kl$), Eq. 3

$$L_w = \frac{\sum n_i c_i l_i^2}{\sum n_i c_i l_i} = \frac{\sum n_i k l_i^3}{\sum n_i k l_i^2} = \frac{\sum n_i l_i^3}{\sum n_i l_i^2} \quad (6)$$

where

c_i = coarseness of each size class.

This expression is frequently adopted, especially by users of the FS-200, but it should be emphasized that it is only valid if coarseness is directly proportional to fiber length. If it is not proportional, the calculation provides only an approximation of L_w .

In the present work, the whole pulp and its fractions were analyzed regarding fiber length and coarseness to compare the results calculated using the given equations.

EXPERIMENTAL PROCEDURES

Sample preparation and classification

Bleached kraft pulp sheets produced from *Eucalyptus globulus* were donated by a pulp and paper mill (Soporcel, Portugal). The borders were trimmed from the sheets, which were then torn and mixed to obtain a composite sample representative of the original pulp. After soaking

and disintegration, the pulp was analyzed by the Kajaani, Galai, and microscope techniques.

Additional tests were also conducted with rayon fibers of 500- μm nominal length (L_n). These fibers are normally used to calibrate the FS-200 with regard to coarseness. Because they are mainly straight, narrowly distributed, and present sharply defined contours, these fibers are also useful for comparing different measurement techniques.

Fiber classification was performed in a Bauer-McNett classifier according to TAPPI T 233 cm-82, using screen sizes of 28, 48, 100, and 200 mesh. The objectives were (a) to test the repeatability of the Bauer-McNett, so that a weight-weighted average fiber length (Eq. 4) could be accurately evaluated and (b) to obtain different length fractions for comparison studies. For the repeatability tests, the Bauer-McNett fractions were oven dried ($105 \pm 2^\circ\text{C}$). Otherwise, they were simply air dried to avoid fiber damage.

Measurement of fiber dimension

Fiber length distribution and coarseness of the nonclassified and classified samples were evaluated using the FS-200 according to TAPPI T 271 pm-91 (3). This was the only instrument available to measure coarseness, and no attempts were made to use the other techniques for this purpose.

Fiber fractions ^b	Mass, % ^c
R28	0.33 ± 0.07
R48	45.05 ± 1.39
R100	39.78 ± 1.30
R200	7.10 ± 0.18
P200	7.74 ± 0.19

^a Average of 20 runs
^b R28, R48, R100, and R200: pulp fractions retained on the 28-, 48-, 100-, and 200-mesh screens; P200: pulp fraction passing through the 200-mesh screen (calculated by difference)
^c Confidence intervals at 95% confidence level

I. Results of Bauer–McNett classification tests^a

pose. A stock suspension of fibers of approximately 0.010% consistency was prepared. Samples were further diluted so that an average of 20,000 fibers was counted in the 500 mL of the analyzed suspension. Triplicate measurements of at least two different stock suspensions were performed for each sample.

The stock suspensions were tested afterwards in the CIS-100 fiber length analyzer. Shape factors of 0.5 and aspect ratios of 0.45 were established to exclude from the measurements nonfibrous particles and those that were crossed, curved, and agglomerated. These values were recommended by the equipment manufacturers and were confirmed by preliminary tests, mainly based on the visual observation of the selected and rejected fibers. The lens magnification corresponded to 12.15 μm/pixel, and the camera factor was 0.81. The operating fiber concentrations were approximately five times those used in the FS-200, with an average of 2000 fibers counted per analysis. Each analysis lasted for about 10 min, and at least five replicate tests were performed for each sample.

Finally, microscopic slides were prepared, and fibers from the various suspensions were sized by image analysis, as described earlier. To allow a more direct comparison of the results obtained with the CIS-100, the same geometric filters were used. However, with the microscope,

Parameter	Nonclassified pulp	FIBER FRACTIONS*			
		R48	R100	R200	P200
L_n (Eq. 1), μm	570	825	655	385	115
L_l (Eq. 2), μm	730	890	720	450	200
L_w (Eq. 6), μm	835	975	790	520	325
Coarseness, mg/m	0.073	0.081	0.065	0.054	...

*The R28 fraction was excluded because of its negligible weight.

II. Average fiber length and coarseness of the whole (nonclassified) pulp and classified fractions as determined using the FS-200

only around 800 fibers were analyzed per sample, corresponding to the cumulative analysis of many slides. The magnification corresponded to 3.32 μm/pixel, and the camera factor was 0.68.

Besides providing fiber length estimates, both the CIS-100 and the microscope were also used to measure fiber widths.

RESULTS AND DISCUSSION

Bauer–McNett repeatability

Table I lists the average results of 20 runs conducted in the Bauer–McNett classifier by two operators, on different days, using the standard procedure. Remarkably good repeatability was achieved compared with that published in the literature (13).

Fiber dimensions

Although this study was mainly dedicated to measurement of fiber length, fiber width and coarseness were also evaluated.

The average fiber lengths (L_n , L_l , L_w) and coarseness obtained with the FS-200 are presented in Table II for the whole pulp and for the various fractions, except for R28. (The quantity in the R28 fraction was small and consisted mainly of fiber bundles.) As expected, smaller screen meshes produced lower average fiber length and coarseness, confirming that classifiers divide the pulp into fractions that vary not only in length but also in coarseness (13). Narrow length fractions were

achieved with the Bauer–McNett classifier, as illustrated in Fig. 2.

Table II also shows that larger deviations are found between the weighted and the numerical averages as screen mesh increases, the result of the large number of fines collected in the finer mesh screens. This substantiates that weighted averages are more meaningful than numerical averages (7, 13).

The calculations of the weight-weighted average length (Eqs. 5 and 6) are based on the assumption that coarseness increases linearly with fiber length, which may not be the case. Therefore, the average length-weighted length (Eq. 2) was used to compare the results obtained with different instruments, since this parameter does not depend on any simplifying assumption. Table III lists this value for each sample, including the rayon fibers. These results are mean values of several independent measurements, with the standard deviation always lower than 2% for both the FS-200 and the CIS-100 (often less than 1% for the FS-200). These values substantiate that both techniques are highly reproducible. The standard deviation was not calculated for the mean value reported for the microscope, since the analyzed data for each fraction were added to a unique database.

The most striking conclusion that can be drawn from Table III is that the FS-200 always gives the low-

est values, regardless of the sample analyzed. These are, on average, 100 μm below those of the CIS-100, except for the reference fibers, where the difference is only 25 μm . This suggests that the discrepancy in the results for the two methods is largely a function of the sample characteristics. Possible explanations for the lower values obtained with the FS-200 may be either the insensitivity of this technique to pointed fiber ends or fiber curvature. The fiber “tail” effect—the result of the lack of birefringence at the fiber ends sufficient to ensure detection—has been mentioned elsewhere (4, 14). Fiber curvature also likely contributed to the lower values reported by the FS-200. Visual observation of the fibers revealed a high proportion of curved fibers. The FS-200 measures the projected length of such fibers (which is obviously lower than the real one), whereas these are excluded from the image-analysis data through adequate geometrical filters.

Smaller differences ($\approx 20 \mu\text{m}$) were detected between the CIS-100 and the microscope for all samples. This was expected, since both techniques are based on fiber visualization and subsequent image analysis, using identical software. Moreover, since the same deviation was also found for the reference rayon fibers, it can be concluded that these differences are independent of the fibers measured and are probably related to the optics of both instruments.

Figure 2 shows typical fiber length distributions given by the CIS-100 and the FS-200. As expected, the distribution for the CIS-100 is shifted slightly to the right.

Concerning fiber widths, large deviations were encountered in the results from the CIS-100 and the microscope, with the widths obtained with the microscope being approximately half of those reported by the CIS-100, as seen in Table IV. As before, the same difference was found for both the eucalypt and the rayon fibers. Furthermore, contrary to the CIS-100, the microscopic

Instrument	Nonclassified pulp	FIBER FRACTIONS*			Rayon fibers
		R48	R100	R200	
Kajaani FS-200	730	890	720	450	530
Galai CIS-100	830	975	810	555	555
Microscope	840	1005	830	570	575

*The R28 fraction was excluded because of its negligible weight.

III. Average length-weighted fiber length (L_l) for whole (nonclassified) pulp, classified fractions, and rayon fibers as measured by the three different instruments, μm

Instrument	Nonclassified pulp	FIBER FRACTIONS*			Rayon fibers
		R48	R100	R200	
Galai CIS-100	30	30	30	30	28
Microscope	16	18	16	14	16

*The R28 fraction was excluded because of its negligible weight.

IV. Numerical average fiber width for whole (nonclassified) pulp, classified fractions, and rayon fibers as measured by the CIS-100 and the microscope, μm

method can detect some changes between the widths of the various fractions. This is a consequence of the greater sensitivity of the microscope because of its higher resolution and, hence, these results will be the most reliable. In fact, they are in excellent agreement with those reported in the literature (16 μm) for eucalypts (15).

Weight-weighted average length
As stated before, L_w is very often calculated assuming that coarseness is proportional to fiber length. To test the validity of this assumption, the coarseness of each fraction was plotted against fiber length, as shown in Fig. 3. Although only three fractions were analyzed (because of practical limitations), the curve drawn through the experimental points does not look like a straight line. Of course, more fractions would be needed to draw definite conclusions. Moreover, the coarseness values should also be confirmed by another technique.

An attempt was made to calculate L_w using the classified pulp fractions, i.e., by applying Eq. 4. This raised the problem of what values should be assigned to L_1, L_2, \dots, L_5 .

Should they be numerical or weighted averages? Clark (13) suggests the use of the weight averages by weight, although TAPPI T 233 (1) does not specify any particular average length. In this study, all fraction average lengths were used, with the results summarized in Table V.

It is obvious from Table V that the values of the last column, which are based on L_w of each fraction, are the most adequate for comparison with the weight-weighted average length of the whole pulp. These findings are valid for both the CIS-100 and the FS-200 and agree with those of Clark (13). Nevertheless, all of the L_w values used in these calculations have an implicit linear relationship between coarseness and fiber length. Thus it is not possible to independently test the consequences of this assumption.

CONCLUSIONS

This work compared fiber measurements from two automated fiber analyzers: Kajaani FS-200 and Galai CIS-100.

The FS-200, besides being considered an “optical method,” is based on an indirect technique that does not

Instrument	L_w measured for whole pulp (Eq. 6)	L_w calculated by Eq. 4		
		L_n (Eq. 1)	L_l (Eq. 2)	L_w (Eq. 6)
Kajaani FS-200	835	670	735	820
Galai CIS-100	910	765	815	880

*The R28 was excluded from the calculations because of its negligible weight.

V. Comparison of weight-weighted fiber length (L_w) as measured for the whole pulp and as calculated by Eq. 4 (based on L_n , L_l or L_w of each fraction*)

allow fiber visualization. Its strongest points are the large number of fibers sized in a short time and the capability of providing additional information about coarseness.

In contrast, the CIS-100 enables on-line fiber observations and, through image analysis, provides information about fiber length and width. Its main drawback is that it analyzes about ten times fewer fibers per unit time than the FS-200.

The results show that the lengths reported by the FS-200 are lower than those of the CIS-100. The differences for the length-weighted average fiber length (L_l) were around 10–20%, depending on the size fraction. The use of microscopic image analysis as reference suggest that the fiber lengths obtained with the CIS-100 are more accurate than those of the FS-200. Nevertheless, microscope imaging also showed that the CIS-100 is not accurate enough to measure

fiber widths, at least for the thin eucalypt pulp fibers used in this study.

Both instruments showed good agreement between the weight-weighted average fiber length (L_w) of the whole pulp and the weight-weighted length calculated from the classified fractions. However, the good agreement that was obtained using the L_w values of each fraction may be misleading, since both estimates are based on the assumption of a linear relationship between coarseness and fiber length. This assumption awaits experimental confirmation.

The study will be extended to pine pulp to see whether the same deviations are observed for long fibers. **TJ**

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KEYWORDS

Eucalyptus globulus, fiber classification, fiber diameter, fiber dimensions, fiber length, fineness, image analysis, kraft pulps, measuring instruments, optical measurement.