This review focuses on fiber analysis methods, where the fibers are carried in suspension. They are photographed in a flow cell and their properties are evaluated by digital image analysis. Three fields of fiber analysis are covered: Fiber morphology, pulp surface chemistry and chemically induced swelling respectively dissolving behaviour of pulp.

For fiber morphology commercial analyzers were compared. On an absolute level the measurement differences between the analyzers varied from 15% to 40%, for some morphological parameters up to 70%. Still fiber length, width and curl results are highly correlated so relative comparison is possible.

An increasing number of publications has has recently been devoted to image analysis based evaluation of surface chemistry respectively chemically induced fiber swelling and dissolving. Considering that research effort it can be expected, that numerous innovations in both fields, commercial fiber analyzers as well as new machine vision based fiber analysis techniques, can be expected in the next years.

**Keywords:** fiber analysis, flow cell, fiber morphology, machine vision.

### Introduction

The rapid development of digital image analysis technology within the last years has lead to a multitude of new applications in the field of fiber assessment. This paper gives a review of analysis methods with special emphasis put on the following:

- **Flow cell based methods.** That means that the fibers are measured in suspension, the fiber suspension is pumped through a transparent flow cell where the fibers are photographed.
- **Application of image analysis.** The review focuses on methods applying machine vision to characterize fibers.
- **Only methods for fibers in a size range up to a few millimeters of length and 100 µm of width are considered.** So the focus lies on pulp analysis, but some methods can also be used for other fiber types.

A Flow cell combined with image analysis is an efficient concept for fiber characterization because the measurement can be carried out in a fully automated manner. Provided that hard- and software are stable enough, such analyzers can be used for online process control, e.g. in the pulp industry. This is the main motivation for the considerable research effort that has taken place in this area within the last years.

In the following the focus has been set on three different aspects of fiber analysis:

- **Fiber morphology**
- **Pulp surface chemistry**
- **Chemically induced pulp fiber swelling and dissolving**
Fiber Morphology

This section first gives an overview of the fiber properties which are commonly summarized under the term fiber morphology. Then six commercially available fiber morphology analyzers are discussed in detail. At the end of this section a quantitative comparison of measurements from the various analyzers as well as repeatability issues are treated.

An overview of fiber morphology features

The morphology, i.e. the structural appearance, of fibers is commonly described by five parameters: length, width, coarseness, kink and curl. Fiber length and width are common features which are fairly straightforward to implement for image analysis [8,14,27]. Fiber coarseness is defined as the fiber mass per unit length, usually in microgram per meter fiber length. It is closely related to the fiber wall thickness of tube shaped fibers like wood. Coarseness is normally determined by producing a fiber suspension with well defined solids content and measuring the cumulative fiber length in a defined volume of this suspension.

Figure 1. Fibers with different curl but same curvature [11].

Please note, that the arithmetic mean may be a bad measure to characterize a population of fibers, especially when the multitude of elements is small (as it is the case for e.g. pulp). Then the mean value is merely determined by the amount of small particles in the sample. For that reason often the length weighted mean is recommended [3].

Fiber kink and fiber curl provide information about the bending of the fiber. Curl describes the degree of non-straightness of a fiber, it gives no information if a fiber bends gradually or abruptly. A multitude of different mathematical definitions for curl is used [11,12,16,22,28]. The commercial pulp analyzers use varying definitions for curl.

Figure 2 Fibers with different kink but the same curl [11].

Although it is reported that the various definitions for curl are correlated [22] the measurement results can usually not be compared. Figure 1 shows fibers with ascending curl, please note that the curl varies but fiber curvature remains unchanged. That is the case because curl, in contrast to curvature, is a size invariant descriptor. Fiber kink [13] denotes small regions of very high curvature, i.e. sharp bends, along the fiber. It indicates fiber deformations, mostly caused by mechanical damage. A fiber with high kink is shown in figure 1 on the right side, the fiber on the left side has the same curl (i.e. overall nonstraightness) but significantly lower kink.

Further fiber characterization parameters are listed in figure 3. Fibrillation describes the number of fibrils, i.e. fiber wall fragments, sticking out of the surface of pulp fibers. Fines content denotes the
number of small fiber fragments. Unfortunately definitions below which size a particle is considered small vary largely between the examined analyzers [2,12,28,30]. Few analyzers evaluate number and size of hardwood vessel cells in the pulp, fiber flexibility or wall thickness. Finally shives are counted, they are bundles of fibers that were improperly disintegrated during the pulping process.

**Flow cell based fiber morphology Measurement**

Now six widely used commercial pulp analyzers from different manufacturers are reviewed. They are all based on a rear illumination flow cell and image analysis. The measurements obtainable, hardware concept and some aspects of image analysis are discussed for each analyzer. An overview of the fiber parameters measured by the devices gives figure 3, figure 4 summarizes some technical specifications.

The Galai CIS-100 [2] is also sold under the name Pulp Fibre Analyzer. The flow cell light source is a pulsed flash, images are acquired by a CCD camera. Length, width and curl of roughly 2000 fibers are measured per pulp sample. The device also gives a value for fiber fibrillation, however neither a definition of this value, nor an empirical verification could be found in the literature. The Metso FiberLab has two light sources, it uses three optical detectors [30]. That enables it to perform a wide variety of fiber measurements. Images from a low resolution camera are evaluated for fiber length, coarseness, kink and curl. Fiber width, cell wall thickness and cross sectional area are measured by a separate high resolution camera. The fiberLab is the only device that offering measurement of these parameters. The third sensor is a light scatter detector used for measurement of smaller particles.

The STFI Fibermaster [12] is a two-camera system providing fine and coarse resolution images. All image processing is hard wired as camera on-chip logic which makes measurements considerably faster than the other systems. The fiber measurement provides length, width, coarseness, kink and two shape factors for curl. Vessel cells are identified and counted, also shive content is evaluated. The Fibermaster is the only fiber analyzer that provides a measure for fiber flexibility [12]. It follows the principle that shear forces (and thus bending stress imposed on fibers) increase with flow speed in the flow cell channel. Therefore flexibility in Fibermaster measurements is defined as the change of fiber curl at different flow rates in the measurement cell. Large changes of fiber curl upon changes in flow speed indicate high fiber flexibility.
The OpTest Fiber quality analyzer (FQA) has a special flow cell design aimed to prevent fouling and forming of deposits. Three currents are lead through the cell, only the middle current carries fibers, the currents flowing next to the wall consist of pure water [29]. Transmitted illumination is provided by a circular polarized laser flashlight, opposed to other flow cells which are using linear polarized light. The device measures length, width, coarseness, kink and curl. Fiber width measurement sensitivity is given as 1 \( \mu m \) although camera resolution is 36 \( \mu m/\text{pixel} \), additional resolution is estimated by interpolation. The FQA also measures shives and vessel content.

The Techpap MorFi fiber analyzer [28] has one high resolution camera. Fiber length, width, coarseness, kink and curl are analyzed. The system gives a measure for fiber fibrillation, it is defined as the length of all micro fibrils attached to the fibers in relation to total fiber length. However an empirical verification for this measure can not be found in the literature.

Finally there is the Kajaani FS-200, which has been on the market since the 1980ies [34] and has been widely used since. Its working principle is totally different from the other devices: The sensor is a line camera aligned along the length axis of a capillary, this capillary carries the fiber suspension. The capillary is illuminated with transmitting polarized light, as the fibers are carried along in front of a sensor element, they induce changes in polarization which are detected by the sensor element [30]. So basically the 1-dimensional projection of a fiber is measured. For this reason only fiber length and coarseness can be measured. As the row sensor has a rather low resolution of 50\( \mu m/\text{pixel} \) fines measurement is only possible to a limited extent.

Repeatability and comparison of results

Repeatability of the above described fiber analyzers [2,5,8,24] is obviously closely related to processing speed and subsequent total number of fibers analyzed, see figure 4. Repeatability on a 95% confidence level according to Tappi standard T 1200 sp91 was between 2% and 5% for (length weighted) fiber length and fiber width. For curl and kink repeatability is not as good, it ranges between 6% and 11%. For Coarseness measurement, which additionally contains the error of determining the solids content of the suspension, repeatability is 10% or worse. No repeatability is given for other parameters.

Comparing the results from measuring the same pulp fiber samples using the various pulp analyzers revealed large differences between the devices.

For fiber length the Kajaani FS-200 has a totally different measurement principle than the other devices, mainly because it measures a 1-dimensional projection of the fibers whereas all other systems evaluate 2-dimensional projections. Consequently the FS-200 measures curled and kinked fibers too short. Apart from one publication [24], this result has repeatedly been confirmed in the literature [2,30,33] and was also found by our own investigations [8]. The MorFi system measures even shorter values for fiber length than the Kajaani [5,30] although it uses a 2D. That leads to the conclusion, that the MorFi system also measures fiber length too short.

Deviations in (length weighted) mean fiber length between the systems was around 15% to 20%, so absolute comparison of results is impossible. However relative comparison of 17 different pulps measured in four analyzers [30] gave highly correlated results. The situation for fiber
Figure 4. Technical specifications of six commercially available flow cell based fiber analyzers.

width was similar, differences in absolute values were up to 40%, still relative comparison is possible because the results are highly correlated.

As mentioned above, different definitions for fiber curl are used by most of the reviewed pulp analyzers. Not surprisingly the curl values between MorFi, Fibermaster and Fiberlab differed strongly [30], absolute difference was up to 70%. Correlations were still fairly good, thus relative comparison is still possible to some extent.

The analyzers do not recognize fine particles in the same way, which comes from two reasons. First there are great differences in optical resolution, from MorFi with 4 μm/pixel to Kajaani FS-200 with 50 μm/pixel. These differences become most relevant for recognition of small particles. Secondly different rules for classification of fines are implemented. As a consequence they measure different amount of fines, which in turn leads to strong differences in coarseness [30].

It does, however not lead to strong differences in average fiber length, because length weighted fiber length was compared, reducing the influence of fines content [8].

For coarseness not only absolute values differed, correlation was also bad [24, 30] thus the results of coarseness measurements from different pulp analyzers can not be compared. That is mainly due to the fact that for coarseness measurement, apart from the error of differing fines results, additional error for determining the (very low) measurement consistency of the suspension comes into effect.

In conclusion quantitative comparison of the results displayed large differences between the fiber analyzers regarding several perspectives. Hardware concept, image resolution and illumination vary largely. It can be speculated that the implemented image analysis algorithms might also be very different. Most important however is the fact, that the measurement results are grossly differing, for some fiber properties they do not even reflect relative ranking. All these facts indicate, that developments in this field are far from being finished. Calibration and standardization of these measurements still needs to be accomplished.

Surface chemistry of pulp fibers

A multitude of dyeing or staining schemes exists for microscopic analysis of pulp fiber surface chemistry [3,16]. Some of them are directly observable [4,25], many apply fluorescence [23]. Apart from staining lignin exhibits strong autofluorescence, when it is excited with light in the wavelength range of 500 nm. This is often combined with Confocal Laser Scanning Microscopy, for example
in order to measure lignin content profiles across the fiber wall [20].
The key point is, that many of these microscopic methods have the potential to be adapted for automated, image analysis based measurement in a flow cell. Several flow cells have been developed for measurement of pitch, i.e. colloids of hydrophobic substances, in pulp suspension. A measurement based on staining with fluorescent dye and laser light was described by [15]. They measure count and size of previously stained resin particles by pumping a colloidal particle suspension through a capillary and evaluating the scatter of laser light. An evaluation of the instrument [35] showed, that reproducible results are obtained, if influence parameters like for example solids concentration and flow speed are controlled. Flow cytometry of bacteria and wood resin particles is also discussed in [32] and [17]. Fluorescence scatter induced by staining of resin and bacteria is evaluated in a flow cytometer (i.e. a flow cell for cell counting). They find very good correlations between bacterial counts performed in a flow cell and counting of bacteria colonies grown on a laboratory nutrient media. Relations between resin agglomeration and bacteria count as well as interaction with carbonate particles are discussed.

A particularly interesting approach to measure the uniformity of Kappa number on a single fiber basis describes [18]. This method stains the fibers with the metachromatic fluorescent dye Acridine Orange. It has been shown that at low lignin concentrations the stained fibers exhibit a green fluorescence, while at higher lignin content they exhibit a shift to red fluorescence. The ratio of red to green fluorescence correlates well with lignin content. Measurement of fluorescence is realized by picturing and subsequent image analysis of individual fibers in a flow cell.

An interesting approach to combine a set of dyes to characterize different types of chemical fiber surfaces has been published quite recently [4]. They use basic dyes for identification of lignin on the surface, basic phthalocyanine dyes for detection of hemicellulosic surface regions and finally direct dyes, which have an affinity for alpha cellulose. Then they evaluate the effect of different laboratory bleaching sequences on the fiber light absorbancy caused by the varying dyes. Principal component analysis revealed two main components representing lignin content and polarity (hydrophilicity or hydrophobicity).

**Chemically induced fiber swelling and dissolving**

Since the 1960ies, the swelling and dissolving process of chemical pulp fibers dissolving in chemicals has been examined [10]. Fiber dissolution in chemicals like iron-sodium-tartrate (EWNN), lithium-chlorine/dimethylacetamide (LiCl/DiMAc) or cupriethylenediamine (CED) starts with intense swelling and proceeds to increasing disintegration of the fiber. These various stages of disintegration of the fiber have a very specific visual appearance [10], for example see figure 5.

Fiber swelling starts with so called balloon swelling (I) where only limited parts of the fiber are swollen, it proceeds to volume swelling (II) where large parts of the fiber wall are already broken apart. Finally it reaches a phase called gel swelling (III), where the fiber has already widely disintegrated.

It has been quite straightforward to observe, that the presence of specific swelling phenomena at lower chemical concentration is related to the ability to dissolve at higher concentration. So fiber swelling has been observed to assess the adequacy of chemical pulp for viscose production. A quantitative evaluation of swelling and dissolving of pulp fibers in EWNN and LiCl/DiMAc has been...
Figure 5. Characteristic types of pulp fiber swelling induced by a chemical agent: Balloon swelling (I), volume swelling (II), gel swelling (III).

implemented [31]. The authors record video images of single fibers dissolving and apply image analysis to evaluate changes in fiber thickness and fiber transparency. Finally they measure the time until the fiber breaks apart. These parameters, together with other laboratory results, are used to quantify swelling and dissolving behavior.

On the other hand, the swelling behavior is largely related to the fiber wall structure [26]. The S2 layer of the wood fiber wall, due to its highly aligned fibril structure, is very prone to swelling, whereas the S1 wall layer with its crossed fibril structure restricts fiber swelling [26]. So chemically induced fiber swelling provides an indirect method to evaluate mechanical and chemical damage of the S1 wall, in fiber regions with heavy swelling the S1 is obviously damaged. Such methods use different chemical agents to promote strong fiber swelling. A CED based method [21] finds good correlations between beating degree and fiber swelling. This method was adapted at our institute, we evaluate fiber swelling using image analysis and a flow cell [5,6,8,33]. A different swelling chemical, iron-sodium-tartrate (EWNN) is used in [9]. The authors examined fiber swelling, fibrillation, nodes of damage and curl index by visual inspection of photographs taken at specified time intervals after addition of the swelling chemical. According to recent work [1], which compared fiber wall damage visualized by polarized light microscopy [7,19,22] to fiber wall damage indicated by chemically induced swelling, both methods indeed indicate cracks in the S1 fiber wall.

Conclusions

The present review shows, that considerable effort has been put on both, academic research as well as commercial development of image analysis based fiber characterization methods. In the field of fiber morphology, there are already several commercial devices available. The measurement results for basic features like fiber length or width show sizable differences in absolute values, still correlations are high. Thus comparison of the absolute values is not possible, relative comparison can be achieved. More complex fiber characteristics like curl or coarseness can not be compared well, neither in absolute nor in relative results. It will be the challenge for the following years to achieve standardization and comparability for these fiber analyzers. Even more advanced features like fiber wall thickness, fiber flexibility and fiber fibrillation are rarely offered yet, but without doubt these are under development by most of the fiber morphology flow cell manufacturers.

For fiber surface chemistry respectively pulp swelling and resolving behavior no commercial analyzers are on the market yet. Still several research groups are working on such methods. To date the potential of these analytic approaches has not been fully tapped. It can be expected, that within the coming years on the one hand some existing microscopic fiber
analysis techniques will be adopted for automation. On the other hand, the fast growth of image analysis hardware and algorithmic capabilities will permit totally new methods and approaches to fiber analysis. For that reason fiber assessment has been a pronounced research focus at our institute during the last years [5,6,8,33]. Various flow cell prototypes with according image analysis software have been developed for pulp fiber quality research.

References


