ON-LINE PAPERMAKING SENSORS: AN HISTORICAL PERSPECTIVE

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ABSTRACT

As the title implies, this paper will discuss papermaking on-line instrumentation, concentrating on sensors for paper quality measurements. The review is intended to explore not just the techniques for measurement, but also the evolution of a particular measurement and the research behind it.

On-line instrumentation will be the primary focus, covering not only the usual structural, mechanical and appearance properties of paper but also certain water system measurements around the papermaking thin/thick stock loop. These measurements will include a discussion of the sensors pertaining to "wet end chemistry" and consistency, with their incorporation into retention control schemes.

Discussion of off-line, laboratory measurements will be included where pertinent to provide a prediction of future on-line sensor availability. The usual papermaking process measurements such as pH, temperature, level, pressure and flow will not be covered.

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To assist the reader, this lengthy paper is broken into a number of chapters, an outline of which is presented below:

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I INTRODUCTION

A Prologue and acknowledgement

This paper is intended to be a review of on-line sensors for the papermaking process. Given that broad definition, some limit needs to be placed on just what is meant by a "papermaking" sensor. To start with, on-line instrumentation for paper properties will be the primary focus, covering the usual structural, mechanical and appearance properties of paper. Paper properties of interest include ash, basis weight, brightness, caliper, coatweight, color, defects, fiber alignment, formation, moisture, opacity, permeability, porosity, smoothness (roughness), stiffness and strength. Stock loop measurements include consistency, drainage characteristics, fiber properties and freeness, along with an emphasis on the "wet-end chemistry" measurements of charge, retention, streaming current and zeta potential. No matter what the sensor, an attempt will be made to show its historical technological underpinnings and the evolution of a particular measurement technique.

Second, in certain cases, the signal produced by the sensor will be incorporated into a discussion of the process control system for the paper machine. These discussions are especially pertinent when the sensor can only measure a compromise element of a true property attribute. An example of this is a scanning sensor, whose purpose is to measure machine-direction (MD) and cross-direction (CD) properties.

Third, some present laboratory-only, or off-line measurements will be discussed, as precursors for the possibility of relating to or someday achieving on-line status. In addition, there will be some discussion of pulp properties and how they relate to, and are predictive of, paper properties. Finally, what will not be covered are many of the usual papermaking "process" measurements, such as flow, pressure, temperature and pH. In addition, such things as felt conditioning, machine vibration, stickies measurement, dirt or ink count, water quality and print quality will not be covered. Selected process measurements – some of which have a direct impact on paper properties or certain machine runnability features, will, however, be addressed.

At the start of my research, the writing of a review of the state-of-the-art for papermaking sensors seemed quite a daunting task. It still does. I thank Dr. Brander and the Fundamental Research Committee for presenting me with this challenge and opportunity. I am indebted to the many people who helped me during the course of my research and writing. First of all, my family, especially my wife Marcia, was especially understanding and patient during the yearlong period when I would disappear into the library or hide behind a computer screen to compose text. Secondly, many of the manufacturers of commercial sensors were of great assistance, providing sketches and discussions of their products, and in many cases editing my erroneous explanations. In certain instances, commercially available sensors are mentioned. No endorsement of these products is intended; their use is for illustrative purposes only. I thank the Departments of Paper Science and Engineering (especially Ms. Laurie Guest, who captured the scanned figures), and the Library personnel at Miami University for their support during the preparation of this paper. Finally, I apologize in advance for those explanations and discussions where I have plainly missed the mark. My native ignorance simply got in the way and prevented reality from intruding.

B History and prognosis

This survey should complement the other surveys of on-line instrumentation for the paper machine. In the early 1980's, Walbaum and Lisnyansky gave an excellent review of many of the on-line instruments for paper quality measurements [1].¹ In the same time period, Pfeifer described on-line sensors for the measurement of basis weight, moisture, ash and caliper [2,3]. In the last 20 years, other authors have written articles describing general sensor trends or surveys and status reports, most with a narrow scope, concentrating on one, or a few classes of sensors [4,5,6,7,8,9,10,11,12,13,14,15,16].

Certain books, which are typically thought of as text or reference books, also contain discussions of papermaking sensors. Notable authors are Lavigne [17], Kouris [18], Smook [19], Biermann [20], Sell [21] and Niskanen

¹Cited references, indicated by [N], listed at the end of the paper in References, are sequentially numbered according to the order in which they were first cited.

[22]. One recent and excellent reference is Chapter 4 of Book 14, Process Control, of the Papermaking and Technology Series published in cooperation with the Finnish Paper Engineers' Association and TAPPI. Edited by Leiviska and authored by Jouni Tornberg, this source discusses many of the special measurements in pulp and paper processes [23].

One might question why we have a particular paper sensor. Historically, many of today's papermaking sensors sprung from the need to quantify a particular performance attribute of paper. A quote attributed to Lord Kelvin is pertinent here:

"I often say that when you can measure what you are speaking about, and express it in numbers, you know something about it...." [24].

To know more about this business of papermaking, removing some of the art and replacing it with science, we have a need for more appropriate sensing applications and quantities of instrumentation. Indeed, some estimates have been made which state that the number of sensors on paper machines has been doubling every three years [25]. With computer use in the paper mill now commonplace and indeed necessary for the running of the machines, it might be worth while to step back some 50 years to review technology.

Post World War II electronic technology had severe limitations by today's standards. Measuring instruments and recorders were galvanometric devices. Audio frequency recorders used steel wire as the recording medium. Calculators were electromechanical, occupying about ½ cubic foot to provide addition of 10 digit numbers. Amplifiers used vacuum tubes, having a life of 1000 hours. Two vacuum tubes per bit of digital information were required, with a power consumption of about 2 watts/bit [9].

Many of today's sensors have evolved from basic concepts that are 50 years old. These sensors and the associated larger systems differ mainly in the development of transistors and use of digital computers, making the sensors more consistent, accurate and reliable. These sensors, along with the communication and manipulation of information in process systems, are allowing real-time process optimization.

Some sensors however are based on entirely new concepts using non-linear and other optical phenomena. These sensors are able to sense newly important process variables, such as pattern recognition systems. Systems for the micro-scale capture and quantification of paper structure are providing valuable insight. Confocal laser scanning enables the examination of paper at the fiber level, and conventional light microscopy is sufficient to view localized surface texture variation, providing a contrasting measurement of surface roughness when compared with air-leak devices. Scanners allow the determination of macro-scale variation in mass density distribution, and with numerical analyses of these images, the papermaker can quantify fiber collapse in a sheet, sheet pores and wiremark. The nature of fiber orientation in a sheet can be obtained, layer by layer, using image analysis techniques that identify individual fiber segments within their larger fiber network. While fiber orientation has traditionally been inferred from ultrasound tensile stiffness measurements, the difference in fiber orientation values given directly by image analysis, when coupled with indirect ultrasound data gives a measure of the contribution of drying strain to sheet MD and CD tensile values.

Smart sensors with built-in intelligence are now interfaced to data highways, communicating with optical fiber links to process simulators so that, for example, heat transfer coefficients can be calculated in real time. Similarly, the reading of sensors in hostile environments can be remotely calibrated and assessed for data reconciliation to assist with maintenance procedures, manage energy consumption and pinpoint problem identification [26]. Relating, and indeed predicting, paper breaks from databases of on-line measurements is an exciting new development. Fuzzy logic based expert systems can identify the possible causes and their associated probabilities for a paper break after the fact, but can also make recommendations to the operator for actions to avoid a break [27].

The papermaker has many new tools in the quest to relate process cause and effect [16]. Much has changed in the past 50 years, from the first on-line sensors installed in the 1950's, to the first computers installed on paper machines in the 1960's, to the Plant Information Systems of today. Even 20 years ago, computer control of properties such as basis weight, sheet moisture and ash content were thought of more as necessities than luxuries [28]. The early 80's provided on-line color monitoring and control, in addition to CD profile control systems [5]. Cross machine control of basis weight and moisture was then, and still is, regarded as one of the most important breakthroughs in paper machine automation.

Sensor and consequent system development will continue, with the demand for more specialized applications [14]. The improvement in paper uniformity and the achieving of better functional properties of paper is a need which will continue. Paulapuro [29] identified those important structural elements of a printing paper which affect quality as formation, fiber orientation, z-direction material, density, bonding, and pore volume distribution. These elements will provide one driving force for sensor development, so that ultimately we achieve on-line measurement and control of paper properties with automatic grade changes, coordinated control of CD profiles, retention, and wet end charge.

About 10 years ago, Kaunonen and Paunonen [30] identified trends in the industry, which were driving automation developments. They described both

"market pull" and "technology push" as providing the impetus for future automation evolution. The "push" from technology was represented as increased computing power, new algorithms (fuzzy logic and neural networks), system openness and integration, along with smart sensor development. The marketplace "pull" stems from environmental pressures, new on-line sensors for paper quality used more aggressively to achieve stable production, and evolution of the operator's role with empirical knowledge incorporated into the process control system. The integration of DCS, quality measurements and information systems will continue to produce a decentralized control system and centralized information system.

While this paper is intended to be a description of sensors and their ability to measure things of interest at increasingly smaller dimensions, the paper producer will continue to strive for higher production rates with the expected adverse effect on paper quality. On the other hand, improved sensing will allow improved uniformity, which then will allow higher production rates. The machine developers must continue to develop paper machinery which helps produce more uniform paper at all dimensions, but particularly at submillimeter sizes - a class about which we know too little. Gradient measurements are important, yet we still know little about high-resolution measurements of fines and filler distribution. MacGregor [31] has classified certain dimensions important in papermaking into three categories, along with available tools for measurement and control. In the centimeter to meter region, CD profiles, streaks, and pulsations are treated by such tools as slice actuators, dilution headboxes, attenuators, piping configuration, scanning and fixed (basis weight, moisture, ash . . .) gauges, and variable crowns. In the millimeter to centimeter zone, formation, fiber orientation, curl, mottle, and coating streaks are treated with soft X-rays, image analysis, ultrasound, stereo microscopy, gloss meters and nuclear magnetic resonance. Finally, in the micron to millimeter class, MD microstriations, smoothness, surface density, porosity and coating graininess utilize the tools of scanning electron, confocal, ultraviolet, acoustic and ordinary light microscopes.

C Sensor organization

It is now time to start the detailed discussion of the various sensors. For organizing the sensors, a grouping suggested by Scott et al., will be followed [32]. Chapter II will describe sensors for structural properties. Structural characteristics describe how the various components are arranged in a sheet. Those properties strongly affected by structure are basis weight, thickness, formation, fiber alignment, and smoothness. Moisture sensors will be placed here because of their close association with basis weight. Basis weight and

moisture sensors will be discussed first, as these were typically the first on-line quality sensors installed on paper machines.

Next, sensors for the mechanical properties of tensile strength and stiffness will be discussed in Chapter III. Included in this chapter will be a discussion of miscellaneous mechanical measurements, break and defect detection systems on operating paper machines, and how pulp properties relate to resultant paper properties.

Sensors for appearance, or optical properties will be discussed in Chapter IV. Opacity, brightness, color and gloss are of interest, but ash and coat weight measurement will be included, since the purpose of these is to enhance the sheet's appearance and receptivity for print. The retention of ash and other fine particles recently has received much attention. Accordingly, Chapter V will present a discussion of the sensors for "wet-end chemistry" measurements, including a discussion of the measurement of consistency and certain retention control strategies.

Each sensor has had its own path of technological development. As suggested by Pfeifer [2], most measurement techniques have evolved in a very similar fashion. First there was an exploratory period where many approaches were developed and tested. A maturation period followed when the successful approaches emerged. Finally, a refinement period occurred when the matured technology was tuned for a variety of applications. As each sensor is discussed an attempt will be made to place it in position along the path of its development.

II STRUCTURAL PROPERTIES

A Basis weight

1 Scanning gauges

Scanning gauges, mounted at the dry end of the paper machine, have, for many years, been the standard method for measuring basis weight, moisture, caliper and ash. No matter what the property to be measured, these scanning gauges produce sparse information about the characteristics of the sheet and suffer from the features of being able to discover only very low frequency disturbances with large dead times in the control loop. Accordingly, much effort has gone into developments to improve this situation, and only lately certain technological breakthroughs have emerged that offer great promise for alleviating many of the problems inherent in scanning gauges. Of all the on-line sensors, basis weight gauges will be discussed first, coupled with a discussion of the technological developments pertaining to scanning gauges in general.

2 Sensors and signal handling

Basis weight is defined as the mass of material per unit area. Occasionally called areal density, the favored unit of measure is g/m^2 . Not infrequently, the unit of measure might be lbm/3000 ft² or sometimes /1000 ft². The on-line measurement of basis weight might be considered to be in the refinement period, given the many years of development and use. While this might be true for the single-point or scanning nuclear radiation gauges, that is not necessarily the case for full-sheet imaging technology, which might be classified in the exploratory period.

As has been true for many years, the primary method for weight measurement is the beta-gauge transmission technique incorporated into a scanning gauge at the dry end of the paper machine. (For non-woven applications, the gamma backscatter technique is also used [33]. Another technique is based on filtered blackbody radiation in the far infrared region [34]. Neither of these techniques will be discussed here.) Beta particles are collimated and focused toward the sheet, attenuated in a nearly exponential fashion which is almost independent of furnish (and coating), and detected [23]. Detection using Geiger-Mueller tubes, proportional counters, scintillator/photomultiplier tubes and solid-state detectors was attempted during the exploration period of 50 years ago. The ionization chamber has emerged as the optimal detector because of its high stability, ruggedness, and ability to be efficiently sized to detect radiation distributed over the relatively large radiation beam.

Efforts early in the exploratory stage were directed toward compensating for mis-alignments of sources and detector and sheet passline (position of the sheet between the heads). Since the interaction of beta radiation with the sheet is both absorption and scattering, mathematical models for attenuation are approximate and geometry-dependent [2].

The maturation and refinement periods saw the incorporation of the gaseous krypton-85 radioisotope for mid-range basis weights and better methods of compensation so that the gauge's output remained relatively insensitive to passline variation, temperature changes, head misalignment, and furnish variation, a need particularly important for recycled fiber use. Heavier basis weights have seen the use of strontium-90, whereas promethium-147 is the isotope of choice for lighter weight sheets.

Additional development work optimized performance in dusty environments and greatly improved accuracy for lightweight products to 0.25% [2,35,36]. The measurement of lightweight products is especially sensitive to



Figure 1 A beta-ray transmission gauge. Courtesy of ABB, Inc.

air temperature, since the basis weight of air is about 10 g/m^2 for an air gap of 10 mm. Multiple scan averaging and suitable Kalman signal filtering have produced 0.1 g/m² two-sigma repeatability for 150 g/m² sheets with a spot size of 13 mm and a 1 ms response time [37]. Other work concentrated on improving construction techniques by borrowing technology from the aerospace industry, and changing the sliding shutter to a rotating drum assembly for better emission containment and reduction of air gap [38]. A schematic of a typical modern basis weight transmission gauge is shown below in Figure 1 [39].

A non-radioactive source basis weight gauge for more specialized applications is depicted below in Figure 2. Used for polymer film and sheet, this gauge with its unique geometry uses the principle of characteristic infrared (IR) energy absorption of one or more materials in the moving web. As shown in Figure 2, an IR source (tungsten lamp) and reflector is positioned below the sheet. A chopper periodically interrupts the broadband IR beam which then passes through the sheet and into the detector assembly consisting of beam splitters, filters, lenses and as many as twelve photodetectors (four are shown). Optimal filter wavelength/bandwidth combinations are

Receiver Design Only 4 of 12 detectors shown Beamsplitter Filter Detector Lens Sheet Source Design Tungsten Lamp and Reflector

Figure 2 The IRPlus Infrared Sensor. Redrawn from a Honeywell-Measurex Corporation brochure [40].

claimed to make it possible to discriminate between the various polymers in a coextrusion [40].

3 Quality systems and process control

Now that we have a signal from our scanning gauge, what is to be done with it? The average of many scans is used for providing routine basis weight control, in spite of the long dead time between the stock pump and dry end. Model-based CD control is used to evaluate controllability and provide online diagnostics aimed at greater production efficiency [41]. The basis weight sensor signal which before addressed only quality issues now forms part of a much larger system, one term for which is an Integrated Monitoring System (IMS) [42]. The value of an IMS system is its ability to associate high frequency quality disturbances with, for example, process pulsations in real time, made possible by the frequency response of current basis weight sensors, being perhaps 1 kHz. The system may also have the capability to signal an alarm for a potentially hazardous situation, such as a bearing failure. Paper machine mechanical vibrations will not be discussed here, but camera-based break detection systems and hole monitors will be, in a later section.

Providing accurate profiles from a scanning gauge in a timely fashion is a challenging objective. Faster scanning and computing will help, but the difficult task of separating the MD and CD variability has been with us for many years and will be discussed next.

- a Handling the scanned signal old and new methods
- 1) Variance and frequency response

Scanning gauges all have the feature of MD/CD interaction because of the diagonal path across the sheet. This shortcoming has been recognized by many investigators who have presented various methods for partitioning the MD and CD variances, one of which is based on Kalman filtering [43]. The relationships between variance statistics, autocovariance functions and the power spectrum are well described in several sources, and are of great importance when comparing statistics from various machines [44]. Common present practice is to identify orthogonal variance components as MD (averages of CD strips or individual scan averages), CD (variance of the averages at individual CD positions), and residual (the rest, which consists of shortterm MD, random, covariance, interactive and measurement error). Of great significance is the assumption that any data set is representative of a population of random variations, that each measurement is independent of the others, that the measurements are independent of the data acquisition methods, and that the process is stationary. Unfortunately, none of these assumptions is strictly true, which makes the comparison of results and claims for control performance questionable [45]. Incorporation of the actual frequency response of the papermaking process and equipment, with variance separation of scanned data needs to be a part of the solution of any control scheme, a facet which is frequently overlooked [46,47,48].

The process generally used to estimate CD profiles from the time-sampled data is Data Box Averaging. Since the signal is averaged over fixed time zones, the effect of the averaging on CD variations depends only on the width of the zone and is independent of scan speed. For MD variations the ratio of sheet speed to scan speed is important, in addition to the width of the zone. Thus,

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when comparing results, one needs a stationary process to justify analyzing MD and CD components as orthogonal and independent of each other, in addition to statistical and spectral analysis computations being made in spatial rather than temporal terms. Data box width and scan speed are significant and important criteria for comparison purposes [49]. Smaller data box widths and higher scan speeds have followed along a time path, yielding better resolution and identification of variation.

2) Mapping, process models and actuators

We now finally come to generating a signal which will cause an effect – the actuator at the wet end of the machine, whether it be a slice actuator or a valve in a dilution headbox. Measurement is carried out at some distance from the actuators, and the effects of sheet wander and shrinkage are concerns for appropriate control, in addition to the actual effect which actuators have on the process. The filtering of MD data allows control to be accomplished for overall weight by adjusting the stock delivery. CD control needs to be accomplished by relating the measurement array to the actuator array, showing how each actuator is projected through the sheet to the scanner. This "mapping" of databoxes to actuators takes into account sheet wander and shrinkage, but also creates errors which are frequently associated with standing-wave instabilities across the sheet [50]. One method of dealing with the distortion of information which occurs with the reconstruction of profiles from scanned data is to use a technique based on the Generalized Sampling Theorem (GST). This is especially useful for higher control bandwidths but suffers from the fact that the best results are obtained with data from either side of the plane of reconstruction [51].

Various investigators have developed methods for dealing with the CD control problem and various components of it. Nuyan et al. [52], has proposed a CD response model incorporating mapping, actuator response and process dynamics to address the paper quality control problem. The intensity of computation has led others to propose data analysis and compression techniques such as wavelets [53], special algorithms for identification of CD processes from bump test data [54], and the use of Chebyshev polynomials and Fourier representation [55,56].

One newer method of data manipulation, whereby two dimensional properties of the sheet can be extracted efficiently for the purposes of process monitoring, control and optimization, is by the use of extensions of a special form of Principle Component Analysis (PCA) known as the Karhunen-Loeve (KL) approximation. This procedure extracts the dominant features of stochastic spaciotemporal data by separating the information content from the random components. As a by-product, significant data compression results [57,58].

b New control and sensing technology

When considering the historical practice in basis weight control of considering the CD and MD control problems separately, one could further simplify the CD behavior by considering the profile static. By borrowing from the minimum variance monitoring criteria for single-input, single-output control loops, methods have also been proposed for monitoring the performance of multi-input, multi-output CD control systems [59]. Even today the best CD control system design is not suitable for controlling variations over small areas of the sheet, but recent developments in sensors (discussed later) and CD control algorithms offer great promise [60]. Indeed, the future of improved CD control hinges not only on improving the sensing, but also on actuators, since a fundamental limit on the achievable CD spatial bandwidth is set by the actuator response. (Dilution headboxes have recently provided another method for improving actuator response.)

A recent approach (in the last 10 years) to CD and MD control considers the wet-end process as a two-dimensional (2-D) dynamical system with two mutually dependent processes [61]. Two-dimensional systems theory has elements ranging from image processing to digital filter design. Recent progress in the field incorporates recursive estimation and 2-D state space models to generate a 2-D predictive controller [62].

Unfortunately, conventional scanning gauges do not give sufficient information to enable the most efficient use to be made of a 2-D framework. Improving both the methods for signal processing and the sensing hardware are required, considering the sparseness of data. Improvements in signal processing, such as inferential measurement procedures that employ missing data techniques, suffer from an assumption of the underlying model of the process. Sparse data estimation, while a valuable tool, is no substitute for denser data. It is fortunate that in the last few years, sensor technology is being developed that allows greater density of information from a web.

One way of increasing density is the use of faster scan speeds. Another approach is to add a fixed full-sheet sensor that gives full 2-D relative information, but whose absolute value is calibrated by the scanning sensor. Examples of this for moisture measurement are the dry-line camera and wet end gamma gauge and SpectraFoil[™] sensors to be discussed later. Another technique is to have several sources and detectors that scan in a framework. Building on that thought, a system being evaluated by the Pacific Northwest National Laboratory, with US Department of Energy funding, consists of a

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fixed, distributed linear Kr85 beta source and an accompanying array of scintillation detectors and optical fibers extending fully across the sheet [63]. Development continues with this system, with the chief problems being a detector averaging time of up to 10 seconds in order to reach accuracy levels of 0.5%, a robust method for standardization, and cost.

1) The sheet shrinkage problem

The current industrial practice for aligning CD actuators and scanners is to perform a bump test by moving a few selected actuators across the sheet. This process usually requires collecting many scans of data because of noisy data and varying machine processing performance, including sheet shrinkage and wander. Various investigators have investigated solutions to this mapping problem mainly from the standpoint of theoretical considerations [64,65,66,67]. A different approach, involving a hardware solution, uses 2-D image analysis to monitor the variations and magnitude of CD shrinkage by considering the detection of wire mark during the forming stage of papermaking. Images containing the marks are generated by transmitted light, captured by a CCD camera image grabber, then processed numerically. The technique involves a two-dimensional Fourier transformation followed by selective inverse transformation of points chosen from the amplitude spectrum [68,69].

2) Full sheet imaging

Almost two decades ago, Walbaum and Lishnyansky identified light transmission for gauging weight as a technology that gives higher time resolution [1]. Several years later, McDonald et al. [70] showed that light transmittance was a practical method for locating sources of MD grammage and caliper variations. Extending that thought to today, a commercial version of a fullsheet imaging system using near-infrared light has been developed by ABB as the AccuRay® HyperScanTM. A series of high intensity incandescent lights with parabolic reflectors directs a beam onto the sheet, and an array of charge-coupled device (CCD) line cameras with a 1024 pixel resolution measures the passage of light intensity through the sheet as shown below in Figure 3. Scan frequencies of 1-2 kHz, a weight range from 30 to 300 g/m², with a resolution of 0.02 g/m² and a CD resolution as fine as 1 mm are claimed [71]. The system uses wavelet analysis and variation pattern extraction for data compression, noise reduction and variance partitioning. Because light transmission differences exist within grades, the HyperScan



Figure 3 The basic components of the AccuRay® HyperScan[™]. Scanned from [73]. Courtesy of ABB, Inc.

signal must be calibrated with a scanning gauge for an accurate measurement [72,73].

B Moisture

The technologies used in gauges for the measurement of moisture are almost as varied as there are flavors of ice cream. Gauges based on many different portions of the electromagnetic spectrum are the rule, but some gauges use the electrical properties of the sheet, its changing opacity, or its response to nuclear radiation for a moisture signal. Typpo reports on a combination caliper and moisture sensor where the sheet is a portion of a capacitor [74]. As the sheet moisture changes, the dielectric constant changes, as does the capacitance, which provides the moisture signal. Most laboratory methods for measuring moisture involve the weighing and drying of the sheet. Wu et al., however, report a method for measuring the moisture profile through paper in the z-direction by using an impedance method [75]. The geometry is similar to that of a capacitor, and impedance is measured at 100 kHz. In yet another method, the MRI technique is being used to study the internal moisture distribution in a pulp sheet [76]. A spin-echo sequence with a short 2 ms echo time was designed and has proved useful at moistures as low as 6%. This writer suspects that continued investigation of the measurement of moisture content with a variety of technologies will continue.

In terms of historical development, exploratory efforts after World War II

involved a number of electromagnetic-radiation technologies leading to the development of radio-frequency (RF) techniques in the early 60's. Development of infrared (IR) technology continued into the 70's and the application of microwave techniques was realized in the late 70's. Some readers may be familiar with devices named the Aquatel and Gigatel that were commercially available during this time period. Most of the RF, microwave, and IR gauges are presently in the refinement stage of development.

Because of the flexibility inherent in the employment of different frequencies and probe geometries, RF and some microwave gauges can be employed at several different locations on the paper machine. Present practice, however, usually (but not always) dictates that the moisture gauge resides in a unit with the basis weight gauge at the dry end, scanning the sheet with IR energy. Thus all of the attendant problems of establishing a true CD profile and robust control that are exhibited by the scanning basis weight gauges also come to bear on the moisture gauge. The RF and microwave gauges are used in the wetter locations, and there are several reasons for this. At the typical 22 GHx microwave frequency, for example, water has over 80 times higher absorption than other sheet components. Thus, for large changes in water content (at the wet end or press), large changes in signal are possible. As the relative amount of water in the sheet is less, so is the change of signal for the microwave gauges, and noise dominates.

Other microwave techniques depend directly on the dielectric properties of water versus cellulose whereby the shift in the resonant frequency of a cavity is measured. But in the case of either absorption or dielectric properties, the measurement of low percentages of water is limited by the fact that the water molecule is tightly bound to the cellulose and is not free to either rotate or align in the applied electric field.

By comparison, the absorption coefficient of water is smaller at microwave frequencies than in the IR range. Thus, IR technology is used only where the moisture content is low (at the dry end), since at higher moisture contents, signal saturation can occur. This effect is reduced for IR instruments operating in the scatter (reflection) mode, as measurements of surface moisture up to 70% can be made with good sensitivity. Included in the equation for almost all moisture gauges has been the necessity for a basis weight measurement of some sort in order to display percentage moisture.

1 Radio-frequency

Most gauges contact the sheet, establishing alternating fields in the sheet as it passes over the gauge's cross-machine electrodes. Due to the combination of interfacial polarization and the water molecule's dipole orientation, the admittance of the system changes with the amount of water present. An RF current detector provides the signal. Compensation for sheet temperature is required, provided by a separate IR sensor. These gauges can be useful with the heavier paper grades at low moisture levels where microwave gauges lose sensitivity. A variety of probe designs (to vary the depth of field penetration) is available to accommodate a wide basis weight range. Because of sheet flutter and the development of microwave gauges, these gauges are not especially popular [11].

2 Microwave

Most microwave gauges, used in the heavier basis weight grades (>100 g/m²), utilize either the principle of cavity resonance or microwave absorption in either a single- or two-sided configuration. They all tend to be in the refinement stage of development. Coupling through the sheet is via the water molecule's dipole rotation and interfacial polarization mechanisms that are a function of moisture content, thus changing absorption and resonance. A typical single-sided arrangement for moisture measurement via microwave absorption consists of a contacting configuration with a generator probe, absorption cell, and detector, as shown in Figure 4 below [23]. A frequency of 22.2 GHz is typically used. These single-sided gauges are somewhat sensitive to contamination buildup, and sheet surface characteristics.

The most popular microwave gauge is the non-contacting, double-sided resonance type. This gauge could be thought of as two non-contacting single-sided gauges, with a microwave source, receiver and half of a resonant cavity on one side of the sheet, and a passive half of a resonant cavity on the opposite side, as shown below in Figure 5. The gauge first obtains resonance by broadcasting at a certain "reference" frequency (about 2 GHz) at which



Figure 4 A typical single-sided microwave moisture gauge. Scanned from [23]. Courtesy of Valmet (now Neles) Automation.



Figure 5 A typical double-sided, resonance type microwave moisture gauge. Courtesy of ABB, Inc.

the water molecule has no effect. This reference frequency has a minimum electric field (due to the use of circular polarization techniques) at the point in the cavity intersected by the web. The gauge then sweeps through a predetermined frequency range, finding the second resonance (the measurement frequency), which varies with moisture content. The presence of water effectively changes the dielectric constant of the system, thus its resonant frequency, and the magnitude of the frequency shift from the reference is used to determine moisture. Typical performance specifications are moisture ranges from 3 to 70%, with an accuracy of 0.3% moisture or 2% of water weight, whichever is greater. Again, these gauges need a basis weight value with dynamic z-axis correction to report percentage moisture and a sheet temperature measurement to meet data sheet specifications [77].

3 Light transmission – dry line observation

Any gauge that measures the CD profile in an essentially instantaneous fashion represents a giant leap forward in terms of simplicity compared to a scanning arrangement. If the gauge also happens to function with a minimum of dead time because of its location at the wet end, this is truly a bonus. One way of doing just this, by measuring the so-called "dry line" of a paper machine, involves the use of a light source for illuminating the sheet and a camera for capturing the image in terms of a surface reflectivity difference [78]. Here the dry-line is defined as when the liquid on the surface of the sheet disappears and the appearance changes from glossy to matte. (Some paper-makers consider this to be the "wet-line" and define the "dry-line" as when the sheet has dewatered sufficiently so that air is passed through the sheet by foils and vacuum boxes.) This technology is progressing from exploratory to maturation to refinement in a rapid fashion. Light sources at different angles have been attempted, with images being obtained with video and CCD cameras. A frame grabber, with computer processing of the images is currently being used for automatic control of dry-line positioning on several operating paper machines [79,80].

4 Gamma backscatter

Another way of measuring the dry line is to use a gamma backscatter gauge. This gauge monitors the total weight of material on the fabric at the wet end. First practically developed in 1984, this gauge can be used to monitor the drainage profile from headbox to couch, replacing blow-off samples [81]. If mounted on a traversing mechanism, the CD profile can be monitored, but again with the attendant scanning problems.

The gauge operates on the basis of Compton Photon Backscatter in which a nucleonic isotope (Am-241) emits low energy photons which are collimated and directed toward the underside of the fabric ("wire"). The photons are backscattered toward the detector in proportion to the total mass of material. The detector, usually a scintillation crystal with photomultiplier, converts the photon stream to an electrical signal. Since the gauge measures total weight, the conversion to percentage moisture requires a fiber bone-dry weight measurement. For the construction of a drainage profile, the consistency of white water samples must be factored in [82].

5 A non-scanning wet end gauge

A recent development only several years old is a non-scanning weight sensor based on measuring the electrical properties of the material on the fabric at the wet end of the paper machine. It is claimed that the weight on the fabric, after the sheet is formed, correlates precisely with the dry fiber weight [83].

Named SpectraFoilTM, the gauge consists of a fixed sending element with grounding electrode imbedded in a zero-angle foil blade which establishes a flux coupling with the sheet above the fabric, as shown in Figure 6 below. For CD profile measurement, an array of up to 512 sensors is mounted across the machine at a typical spacing of 25 mm, operating at 1 kHz. Approximately 500 full-width scans per second can be obtained with this arrangement. For



Figure 6 General concept of a SpectraFoil[™] sensor. Redrawn from [85]. Courtesy of the Honeywell-Measurex Corporation.

MD drainage profiles and wet-end pulsation monitoring, single sensors can be mounted in foils and vacuum drainage elements from the forming board to the dry line.

Since the electrical properties of the suspension on the fabric changes in a non-linear and dynamic fashion with temperature and chemical composition, a set of reference cells is provided to compensate for these effects. The reference cells measure the electrical properties of the white water doctored from the underside of the fabric and potentially can also be used as an indicator of the chemical and charge balance of the machine [84].

Calibration of the gauge can be done off-machine based on the specific conductivity of the furnish, but this method does not take into account the effects of the fabric and the fiber distribution through the sheet. A better method is to perform a drainage study on the machine using a back-scatter gamma gauge [85].

6 Infrared

When thinking of gauges for infrared (IR) moisture measurement, one usually thinks of scanning gauges at the dry end of the paper machine. Indeed, this highly refined technology is the present practical configuration, usually operating in the transmission mode. During the exploratory period of the 1960's, IR technology progressed slowly because of intrinsic instability in some of the basic sensor components. By 1970, following concepts borrowed from spectrophotometry, the IR gauge evolved into a configuration with a single detector with high stability and self-compensation for drift. A rotating filter wheel provided narrow bands of radiation to illuminate the sheet with AC coupling and amplification of the signal.

Infrared absorption causes vibrational resonance of water molecules. So if IR energy is broadcast at a moist sheet, some is reflected, some is transmitted, and the rest absorbed, depending on frequency. In very simple terms, IR gauges use two wavelengths, one which is strongly absorbed (at about 1.95 microns), and the other which is not, called a reference wavelength (about 1.8 microns). What is measured is the ratio of detected signal strengths, which is then a function of moisture. The signal at the reference wavelength provides compensation for changes in source intensity, detector response, and sheet characteristics. Manufacturers typically use two additional channels of IR energy for increased accuracy and applicability [23].

The decades of the 70's and 80's saw maturation and refinement of the IR measurement technique. Because optical radiation can be easily reflected and refracted, these gauges were easily made insensitive to mechanical misalignment, but this was not the case for changes in sheet composition. The IR absorption phenomenon is unfortunately secondary to scattering interactions provided by the fiber interfaces within a sheet. Thus variations in scattering coefficient and basis weight change the path length of radiation and thus the measurement sensitivity. By redirecting a portion of the radiation back into the sheet multiple times, compensation for path length variation is provided. The presence of a broad-band absorber, such as carbon black, causes special problems. Compensation for this effect is provided by measuring the absolute intensity of the reference beam and adjusting the gauge's sensitivity. Since the moisture gauge's output signal is non-linear, signal processing has also been a substantial challenge. The recent advances in microprocessor computer power have allowed refinement of the gauge to its present levels, and work continues to expand the moisture range for IR transmission gauges by employing special algorithms and models [86].

a TRANSMISSION

One type of transmission gauge uses two specular reflecting hemispheres located on each side of the sheet, as shown below in Figure 7 [87]. Infrared energy from a quartz halogen lamp is focused into the spherical optical cavity, making many passes through the sheet before detection. A number of IR wavelengths are captured and analyzed, eliminating the need for basis weight measurement to calculate percentage moisture. The gauge operates over a wide range of specific scattering coefficients. Sensor accuracy of 0.1% moisture is claimed for a basis weight range of 10 to 450 g/m², with a measurement spot size of about 10 mm.

Another type of transmission gauge uses a slightly different geometry, as shown below in Figure 8. A collimated IR beam is directed at the sheet which



Figure 7 Arrangement of the AccuRay® Smart HemiPlus Moisture Sensor. Scanned from [87]. Courtesy of ABB, Inc.

absorbs and scatters the beam to produce a diverging cone of radiation from the other side of the sheet. An integrating sphere captures this IR radiation, averages it, and sends it to the PbS detector. It is claimed that the use of a "fiber filter" makes it possible to measure percentage moisture without a basis weight sensor [88].

The final transmission IR moisture to be discussed is shown below in Figure 9. This gauge is claimed to be applicable for a wide range of products from lightweight papers to highly filled and coated papers, newsprint and papers containing carbon. A basis weight measurement is required for percentage moisture determination, with the gauge exhibiting minimal sensitivity to changes in sheet temperature, moisture stratification or passline



Figure 8 A single-hemisphere infrared transmission moisture gauge. Scanned from [23]. Courtesy of Valmet (now Neles) Automation.

variations. A halogen source emits broadband IR energy into the sheet gap, where the beam is reflected between quartz plates above and below the sheet. Greater signal sensitivity is achieved via multiple absorption paths through the sheet because of the 5 cm MD offset between source and detector assembly. In addition to the reference and moisture detectors, a third detector, located directly opposite the source, provides information on the sheet's scattering power. The manufacturer claims that integrating this measurement with moisture and reference measurements allows elimination of the effects of varying basis weight, refining, ash level, carbon content and coat weight. Instead of spinning filter wheels which results in measurement of each channel at a different spot on the sheet, this gauge continuously measures all channels, allowing CD resolution of 10 mm with moisture variations at 200 Hz for high-frequency process monitoring. Specifications for this gauge include a moisture range of 0-30% at basis weights up to 400 g/m², with a time constant of 0.8 ms [89].



Figure 9 The Precision[™] Moisture Sensor. Redrawn from [89]. Courtesy of the Honeywell-Measurex Corporation.

b Reflection

A typical single-sided infrared gauge is mounted in a single head package, with a halogen source focused on the sheet. Part of the beam is absorbed and part is reflected (scattered) back, collected and detected. This scatter-mode



Figure 10 The AccuRay® Smart Reflection Plus Moisture Sensor. Redrawn from [90]. Courtesy of ABB, Inc.

technique measures total sheet moisture for lighter grades, perhaps up to 100 g/m^2 , and surface/stratified moisture for others, which may or may not be representative of the true average. A typical gauge, applicable to a wide range of products, is shown below in Figure 10.

Reflection gauges can be used at higher moisture levels (up to 70%) than transmission gauges, and have historically been thought of as insensitive to basis weight, since the sensor "sees" only to a finite depth of the sheet. Assuming no significant amount of energy passes through the sheet, the reflection sensor can be calibrated directly to percent moisture and does not require a basis weight measurement. For basis weights below 100 g/m², where the amount of energy passing through the sheet is scattering-dependent, grade-dependent calibrations can be used to provide good accuracy. The gauge depicted in Figure 10 above uses the analysis of multiple IR wavelengths to provide basis weight insensitivity, and the manufacturer also claims gauge insensitivity to carbon black, passline variations, scattering properties of the sheet, sheet surface smoothness and dust on the sensor window. Resolution of 0.1% moisture is cited with an accuracy of 0.25% moisture [90].

c Caliper: yesterday and today

The on-line gauge for the thickness, more frequently called caliper, of paper, is claimed to have been invented at Consolidated Papers, Inc., Wisconsin Rapids, WI in the late 1960's. A traversing system with contacting heads on either side of the sheet, caliper was measured using the principle that magnetic reluctance varies approximately linearly with paper thickness, and thus inductance varies inversely with thickness. The system often broke the web, since the applied pressure was that required by TAPPI standards [9].

The period of the 1980's saw caliper measurement enter the maturing stage with a variety of concepts having been explored. Ideally, caliper measurement can be done in a non-contacting fashion, with radiation absorption, gamma ray backscatter, inferential microwave techniques, or IR proximity devices. These technologies require that the material to be measured have uniform density, which paper does not, or they suffer from insufficient accuracy. So contacting and semi-contacting gauges were the recipients of continued development. One technology that saw continued development was the double-sided magnetic reluctance sensor, with sheet contact pressure being reduced by one order of magnitude from TAPPI standards, but utilizing a special calibration because of the non-linear pressure-to-thickness relationship [1].

Another similar, but single-sided technique utilized a metallic reference plate over which the sheet slid, held with a vacuum plenum, and a floating head on the opposite side of the sheet. The floating head had holes in it from which high-velocity air escaped, creating an air bearing which was precisely controlled. A proximity transducer in either the floating or contacting head developed a RF field, which was attenuated by eddy currents due to the proximity of a metal target in the opposing head. The degree of electromagnetic coupling, and thus the effective impedance of the system, was a function of the separation between the transducer and the metal target, a portion of which was the paper. Substantial development effort was devoted to self-stabilizing floating-head geometries, and reference plate designs for light, constant sheet contact [2].

The refined gauges of today all rely on magnetic coupling, generating a signal for caliper via oscillator resonance frequency that is related to head separation. Similar specifications by the major manufacturers are claimed: frequency response of 1 kHz, accuracy of 1 micron, a lower measurement range of 20 microns, and a spot size of about 15 mm. One gauge is shown below in Figure 11. This gauge has one floating head, with contact pressure measured and controlled simultaneously.

Another gauge is shown below in Figure 12. This gauge has two gently



Figure 11 A single-floating-head magnetic reluctance caliper gauge. Scanned from [23]. Courtesy of Valmet (now Neles) Automation.



Figure 12 The AccuRay® Smart Caliper GT Sensor. Redrawn from [91]. Courtesy of ABB, Inc.

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contacting ceramic sensing planes supported with lightly-applied air pressure, and wedge-shaped guiding geometry. When air pressure is removed, the planes retract with the assistance of springs in the air channels [91].

D Formation, Fiber Alignment (Anisotropy) and Flocculation

1 Introduction

The non-uniformity of paper should come as no surprise to anyone who considers the materials from which it is composed and the processing which it undergoes. Papermaking furnish, composed of particles ranging in shape from threads to spheres, having different densities and chemical compositions, is accelerated to a high speed, then subjected to several different water removal processes in different directions.

The uniformity with which fibers and other solid components are distributed in paper determines its "formation." In practice, however, formation refers to the appearance of the sheet when viewed by transmitted light. Good formation results when the fibers are evenly distributed, presenting a "ground glass" appearance. Poor formation, with unevenly distributed fibers, yields a mottled appearance. The mottled appearance is caused by clumps of fibers that have formed flocs, which is a function of both the mechanical and chemical characteristics of the fibers themselves and how they have been processed. Unfortunately, the color and optical properties of the sheet also affect the visual evaluation of formation so that two papers that have identical material distributions can exhibit different "lookthroughs." Thus, formation might be labeled an *appearance* property, but because it is so strongly affected by fiber distribution, it is treated here as a *structural* property.

Another structural aspect of paper is the overall alignment of fibers, sometimes generally referred to as "directionality." While few of the fibers in a web have their axes aligned in directions other than parallel to the plane of the sheet, most, but not all are aligned in the machine direction, resulting in anisotropy. Sometimes a preferential orientation exists at some small angle (called a polar angle or orientation angle) to the MD as a result of forces exerted during forming and drying. Absence of directionality in terms of orientation angle is especially important in converting and printing operations, as is another property: "squareness," or "orientation index." While not absolutely the same as fiber alignment, this index is the ratio of sheet strength along the major polar axis divided by that along the minor axis of the strength ellipse. For a zero polar angle, this equals the MD/CD strength (sometimes modulus) ratio [22,32].

Final sheet formation is certainly affected by the propensity of the pulp to

flocculate. A brief discussion of flocculation and forming research will be presented at the end of this section.

2 Formation

a A bit of history

The routine evaluation of formation is based on visual examination (holding a sample up to the light), with quantitative determination made by comparison with several standard samples. No wonder then that most instruments for measuring formation use transmitted light for presenting results. But what exactly are these instruments measuring, and how does that relate to something that counts, such as strength, appearance, runnability or printability? The formation of the sheet ultimately affects all those things, and a phrase such as "the uniformity of basis weight distribution" might be the best descriptor of formation. Still, formation measurements by optical systems do not measure basis weight variation, but small-scale variations in opacity. Correlations between areal mass and optical densities in paper have been studied [92], but still, these measurements are influenced by local differences in the scattering coefficient, and suffer from low resolution at higher basis weights [23].

Indeed, while most of the formation instruments claim to use "uniformity" as a criterion for a formation index (or some similar term), some questions remain. What is the size of the smallest element of interest? What total area should be analyzed? How can the variation be described in a quantitatively representative, simple way? As Ingman [93] has said: "... will we ever get it right?"

The measurement of formation has moved along the path from "art" to perhaps "science" accompanied by friendly controversy and sometimes heated discussion [94]. What today would perhaps be an exchange of e-mails, in the mid 1980's was a series of "Notes to the Editor" of TAPPI by Otto Kallmes, Byron Jordan, and Bo Norman, arguing the merits of formation measurement by image analysis or line-scan power spectrum analysis [95,96,97]. Both technologies are in use by present-day instruments.

One of the earlier formation testers was developed at the QNS Paper Co. The QNSM formation tester was the result (the M stood for Mead Corporation, which participated in the development). A paper sample was placed inside a transparent plastic drum and spun. A light source on the inside and an optical system on the outside traversed the axis of the drum. The detected light signal was analyzed by a frequency spectrum analyzer and displayed on a chart of amplitude vs. frequency (perhaps floc size?) [9]. The spectral density, however, was not transformed simultaneously with the frequency, thus the physical property of a power spectrum to represent the variance contribution within different ranges was lost. Still, the curves gave an indication of the distribution of variance between different floc sizes (wavelength ranges) [98].

The period of the 70's and 80's saw the evolution of a number of formation testers from both the manufacturers and research laboratories. Valmet had an on-line tester on a paper machine in 1973. From the PFI in Norway, a He-Ne laser-based sensor was developed and installed on paper machines between 1978 and 1982. AccuRay (now ABB) developed a formation/opacity/ brightness sensor, the OptiPak[™], in the early 80's which used a double-spot measurement instead of the more conventional single-spot technique. The two detected signals were compared to provide a relative optical density calculation. A formation index was then quantified by evaluating the optical density differences between the various spots and their surroundings on the sheet. This formation index has a good correlation to the basis weight coefficient of variation when measured for one millimeter samples. The Lippke Formation Tester, installed on several machines in Europe and Scandinavia, used a high-intensity laser light to examine a small spot on the sheet. The sensor signal was fed to four digital frequency filters and analyzed to generate a floc size distribution classification of 2, 4, 8, and 16 mm sizes [6]. Even thermovision cameras were installed on paper machines immediately after the slice during this time. The cameras were intended to measure variation in formation induced by cold-water temperature variations [1].

b The technology of today ... and the future?

Most commercial instruments rely on transmitted or scattered light to evaluate formation, usually citing a "formation index," but the methods of handling the signal and the ways in which the data are presented differ widely. The most common quantitative index, the standard formation number (FN), is the standard deviation of local grammage divided by the mean. Another formation number, Dodson's, compares an ideally formed sheet with the sheet to be evaluated [99,100]. Yet another is a threshold equal to the mean grammage, calculated by determining the ratio of the sum of floc perimeters for the sheet to the size of the sheet.

Another method for sensing formation combines beta radiography and video-image processing. From the digitized image, basis weight maps of the sample are obtained, and the Spatial Gray Level Dependence Method is used to characterize formation in terms of textural properties [101,102].

The heated discussion of 20 years ago has cooled somewhat, but different researchers in the field are still continuing along different paths, and the

research laboratories around the world have continued to study formation, considering both new technologies and the comparison of instruments [103,104,105]. Bernié and Douglas [106] reported on a method based on light transmission with image analysis for sheets 20 to 75 g/m^2 with a resolution of 0.1 mm and an accuracy of 0.5 g/m^2 . Local opacity is converted to local basis weight, and a fast Fourier transform extracts the contour map of the flocs. A Floc Formation Index is generated by processing the power spectrum data, analyzing a grid of pixels seen as a grammage matrix. In another study with linerboard, these researchers concluded that there is a necessity to describe the quality of formation as a function of the scale of formation, something that, in 1998, they claim no current formation tester did [107]. Many commercial instruments attempt to collapse the information regarding the complexity of sheet structure and the local nonuniformity of grammage by reporting some single number to characterize formation. These instruments are most likely insensitive to the changes in sheet formation emanating from parameters of the forming process [108,109].

A main factor that hampers suppliers of these on-line instruments is the lack of a good control mechanism to optimize formation in real time. Without such an integrated control loop it is difficult to show an attractive return on investment for capital investment in on-line instrumentation.

Another method for determining formation was reported by Bouydain et al. [110]. Contending that the various methods using statistical analysis of the power and wavelength spectra (along with those of second order statistics that treat paper as two-dimensional) are inherently flawed, they used wavelet decomposition of the light-transmission image of paper to analyze the floc distribution. They claim that this multiresolution method gave better discrimination and selectivity than the standard formation number for analysis of the flocculation at difference scale sizes.

c The sensors

The many sensors that measure formation and also report fiber orientation will be discussed here – not in the section on fiber alignment.

1) CyberMetrics[®] FS2D[™]

This is the successor to the F-Sensor which used the variation in transmitted light from a He-Ne laser to develop a formation index. The F-Sensor was mounted in a fixed position on the paper machine as a U-frame of about $\frac{1}{2}$ meter in length, and flocs or variation in floc density would cause signal variation in the detector on the opposite side of the sheet. The

root-mean-square (RMS) value of the signal was used as the formation index, with larger numbers indicating worse formation.

The FS2DTM is similarly mounted on a U-frame, but uses strobed white light detected by a camera on the opposite side of the sheet. A sheet gap of 100 mm is typical. The video image is analyzed for the pattern of light (low density), dark (high density) areas and floc size. The data is measured as an energy value for a floc size distribution of up to 6 different size classes (typically 1, 2, 3, 6, 10 and 16 mm). The formation index is derived from the total energy value.

In addition to reporting the average floc size, anisotropy of the formation and angle of orientation of the flocs, 3 periodic marks can be followed. The intensity, angle and frequency of streaks and web marks can be tracked. The measured area is 144 cm², with a sampling frequency of 2 images/s, for a basis weight range of 15 to 300 g/m² and a resolution of 250 μ m [111].

2) Measurex[®] SpectraForm[™]

This SpectraFormTM sensor is mounted with other sensors (usually basis weight, moisture) at the dry end and scanned across the sheet. The sensor measures light transmission through the sheet to determine floc size and intensity, reporting small scale basis weight variability (intensity) in each of six floc size cells bounded by 1, 2, 4, 8, 16, 32 and 64 mm.

As depicted below in Figure 13, the source is a tungsten halide lamp with a quartz light pipe. Light passing through the sheet is detected with a silicon photodetector through a 1 mm diameter sapphire light pipe and sheet-contacting dome. Floc intensity is obtained by determining the coefficient of variation (CV) of grammage. Here the RMS value of the AC signal is converted to DC, multiplied by a slope factor dependent on basis weight, then divided by basis weight to obtain the CV of grammage.

The larger the floc intensity, the poorer the formation. Floc size in mm is determined by counting the AC signal crossings from a negative to positive value per unit time, then dividing this value into machine speed [112]. Specifications include a basis weight range from 20 to 500 g/m², a process speed from 110 to 1500 m/min, and a spatial resolution of 1 mm [113].

3) AccuRay® OptiPak™

In principle this sensor is similar to those mentioned above, in that it measures light transmission, except the sensor package includes opacity and brightness measurements, and will be discussed in detail in Chapter IV. Sheet contact is maintained on one side. AccuRay has invented a term called a



Figure 13 A schematic of the Measurex[®] SpectraForm[™] formation sensor. Redrawn from [104]. Courtesy of the Honeywell-Measurex Corporation.

ROD. One ROD is a difference of 0.001 in the relative optical density between a small area of the sheet and that of the large area surrounding it. RODs have a good correlation to the basis weight coefficient of variation for samples having a diameter of one millimeter. Specifications include an accuracy of 1 ROD, a resolution of 0.1 ROD, and a repeatability of 1 ROD. A measurement range from white paper to 99% opacity is claimed [114].

4) WebForm[™]

WebFormTM is a system consisting of a fixed (up to 4 in the CD) white light source, focusing lenses and fiber optic light guides directed to photodiodes, as shown below in Figure 14. Light reflected from the moving web is focused onto the ends of the light guides that are arranged at predefined CD positions in a linear array. A gap of 60 mm from the sheet is typical.

A sampling rate of 32 kHz is used with a spot size of 1 mm to provide a formation index from a power spectrum presentation and analysis. For high speed machines, this sampling rate provides a resolution in the MD of 2 mm. The values obtained using this device relate to the degree of variation in sheet structure at a range of scale sizes in the MD (and at predetermined widths in the CD). Defects are categorized at scale sizes from 1.5 mm to 24 mm in the MD for four particular sizes in the CD, (<3 mm, 3–6 mm, 6–12 mm, 12–48 mm) [115,116].



Figure 14 A schematic of the WebForm[™] system. Scanned from [115]. Courtesy of JH Instrumentation Ltd.

5) M/K On-Line Formation Tester

This device is similar in physical arrangement to the F-Sensor mentioned above. A fixed U-frame holds a white light source about 6 mm from the sheet, about $\frac{1}{2}$ m in from the edge. The transmitted light detector is held about 35 mm from the sheet, viewing a spot size of 1.5 mm in diameter.

The data points are collected and stored in up to 64 "weight" classes, each differing in optical density by about 1% on the gray scale, thus producing an optically-determined basis weight histogram. The Formation Index is determined by dividing the number of data points in the mean weight class (Peak Height) by the number of contiguous weight classes (bins) with at least 100 data points. The more uniform the sheet, the larger the Peak Height and the fewer bins [117,118]. M/K Systems also offers a variety of off-line formation and fiber orientation testers, utilizing transmitted light, reflected light and beta-ray sources [119].

6) Neles IQFormation

This sensor also uses a high intensity light source that is flashed 10 times per second, passing into a fiber optic bundle, then to a source diffuser plate. The

image size is 47×77 mm, and illumination is controlled so that 50% of the pixels are brighter than the midpoint of the gray scale. The transmitted light is detected by a CCD camera which converts the web picture to a 512 × 480 pixel image with 256 gray scale levels. Small 6 × 6 pixel areas are compared against larger 36 × 36 pixel areas for variation in light intensity in a manner based on the laboratory Kajaani Formation Analyzer. The basis weight application is from 20 to 122 g/m², with an accuracy of 1 Formation Index unit and a resolution of 10 mm [120].

7) Lippke (now Honeywell-Measurex)

This sensor is mentioned here because it was one of the first to be commonly used in the European and Scandinavian papermaking community in the mid-1980's. A transmission gauge with a high-intensity (3 MW) laser diode source, the detected signal was subjected to frequency analysis to obtain a distribution of floc sizes in bins of 2, 4, 8, and 16 mm [121]. The frequency analyzer consisted of four digital filters with a bandwidth of one octave each – achieving a range of four octaves. The frequency stored in the detector signal was determined by the ratio of web speed to floc size [6].

3 Fiber alignment

a INTRODUCTION

To review and clarify terminology, definitions for the various terms that are used to describe fiber alignment such as orientation, sheet anisotropy, orientation angle and orientation index will be explored. For an ideal handsheet the fibers are perfectly, randomly distributed, generally in the plane of the sheet. In this case the orientation is 1:1, the orientation angle is indeterminant, there is no sheet anisotropy, and the orientation index is 1. A plot of fiber population versus angle (called a polar plot, usually referenced from the MD) is a circle and the sheet is "square". Now consider the case where there are twice as many fibers in the MD as CD. Here sheet anisotropy exists, the sheet is no longer square, the orientation is 2:1, the orientation index is 2, and the polar plot of fiber population is an ellipse (major axis is twice the minor). The angle that the major axis of the ellipse makes with MD of the sheet is the orientation angle, which may or may not be zero. Thus a sheet which has anisotropy also is "oriented", has "orientation" and an orientation index [22].

Alignment of the fibers is one of the most important factors in sheet runnability through converting equipment, presses, and copy machines. Curl, twist, misregistration and other runnability problems are even worse when fiber alignment on one side of the sheet differs from that on the other side.

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Independent of floc size, an increase in orientation index will degrade measured formation [122].

One method for measuring fiber alignment is to count dyed fibers and their respective angles, constructing a polar plot of average fiber orientation (now done by image analysis). Another method, though indirect, is to subject the paper to zero-span tensile testing, assuming that alignment and strength are directionally coincident. (Evaluation of paper anisotropy is also available from ultrasonic velocity measurements. This technique will be discussed in Chapter III, Mechanical Properties.)

Other indirect methods for measuring the distribution of fiber orientation rely on the interaction between the local structure of paper and light, or other forms of radiation. Holographic interferometry via bending wave propagation has been used to detect anisotropy and orientation angle [123], and special operators from the theory of texture image analysis are being used to evaluate anisotropy from graylevel images [124]. A technique for determining fiber distribution in the z-direction by using confocal microscopy and image analysis has been reported, but is restricted to the top 50 μ m of the sheet [125].

In the X-ray diffraction technique, the distribution of orientation of the crystalline regions of the fiber is measured by rotating a sample in the plane perpendicular to the incident beam. The intensity of scattered radiation (correlating to fiber orientation) is recorded as a function of sample orientation. Fiber orientation can also be measured with light diffraction by basing the measurement on the fact that the pattern for a longitudinal object (such as a fiber) has maximum intensity in the direction perpendicular to its axis. This technique suffers from multiple scattering if the sample is not split into thin layers.

A light reflection technique for sheet anisotropy was examined with the widely-used 45/0 reflectance geometry with a goniophotometer. Light reflected from within the sheet was sufficiently diffuse that it contributed little to the anisotropy. However, the specular component of the reflected light, attributed to reflectance occurring at the facet planes of the fiber edge, was found to be linearly related to the MD/CD stiffness ratio [126].

Light diffusion has also been used for fiber orientation by focusing a laser beam on a small area of the sheet (ca. 1 mm²) and measuring the transmitted pattern on the back side of the sample. The anisotropic pattern has the strongest intensity along the direction of the strongest fiber orientation. This technique was the basis for the Lippke sensor [127] which used the light diffusion principle by focusing a small circular beam of a semiconductor laser with a diameter of about 0.1 mm on the moving web and measuring the pattern on the opposite side with a detector array in a non-contacting
fashion. The signals were analyzed using a mathematical model to yield fiber orientation distribution from the approximate elliptical shape of the energy pattern [128].

Yet another method uses microwaves to measure the dielectric coefficient anisotropy of paper, which is related to fiber orientation. Perhaps more useful for heavier papers, spatial resolution has been poor [129].

A less cumbersome and more direct (and non-destructive) technique than either the dyed-fiber counting or zero-span testing method mentioned above is based on the optical polarizing properties of paper measured with a submillimeter (or far infrared) laser. The laser (ca. 70 μ m wavelength) is linearly polarized and the ratio of transmitted to incident energy is measured at various angles between the MD and the plane of polarization by rotating a sheet sample. The ratio of the maximum to minimum energies correlates to the orientation index, revealing sheet anisotropy. Since this technique is based on absorption (also measuring basis weight), it measures the entire sheet and not just the surface, but is valid only if both reflection and scattering of the laser are small by comparison [130]. Another limitation of this procedure is that incorrect results are obtained if the fiber orientation angle is not zero (the polar plot is not symmetrical about the MD). Finally, this method does not permit the determination of either z-axis variation of fiber orientation or surface orientation [131].

Researchers interested in this far-infrared technique have continued their laboratory efforts into the 1990's on dielectric sheet material. They used a synchronous polarization technique to now enable determination of orientation angle and eliminated the need to rotate the sample by rotating the plane of polarization of the laser [132].

For the reader interested in a tutorial on the methods of determining fiber orientation and the papermaking process implications, which result from attempting CD control of fiber distribution, the reader is referred to an article by Shakespeare [133].

b AccuRay® Smart Fiber Orientation Sensor

This device measures orientation angle (fiber angle) and anisotropy (fiber ratio) using AccuRay's patented Laser Arc PolarizationTM measurement principle on both sides of the sheet, as shown below in Figures 15a and 15b.

A laser on each side of the sheet is fired at the moving web 36,000 times per second, and the shadow pattern of the reflected light is used to deduce fiber alignment characteristics. As shown below in Figure 15b (and the lower left circle of Figure 15a), if all the fibers in sheet 104 are perfectly aligned in the

Measurement Methodology



Figure 15a Detail of the AccuRay® Smart Fiber Orientation Sensor. Courtesy of ABB, Inc.



Figure 15b Arc generation geometry for fibers aligned in the MD with the AccuRay® Smart Fiber Orientation Sensor. Scanned from [134].

MD, when laser 102 is fired, a semi-circular arc of reflected light 106 is formed, and detected by sensors 110 and 112. Conversely, if all the fibers are perfectly aligned in the CD, a straight line of light is formed (as shown in the lower right circle of Figure 15a). For actual machine sheets of course, neither of these conditions is true, and the shape of the reflected arc is warped. In order to determine the generally elliptical polar distribution function for fiber orientation angle and anisotropy, the light simultaneously incident on the sensing region is electrically separated to correspond to optical paths defined by the three light sources. The resultant arc is approximated by an expression which is solved to determine the fiber orientation plot [134].

Sheet flutter is controlled by a stabilizing film of air. Specifications include a claimed accuracy of 0.05 for orientation index, 0.5° for orientation angle, and a 0.2 ms response time. A measurement circle of 5 mm is used, with a basis weight range of 30 to 500 g/m² [135].

4 Flocculation and forming

The flocculation tendency of pulp is tied to the fibers' charge characteristics, their chemical and mechanical properties, and the hydrodynamics of the forming process. Understanding of flocculation is important in the design and operation of the wet end of the machine and plays a major influence on the formation quality of the final sheet. A few of the devices used to measure flocculation will be mentioned here in the hope that future devices for measuring formation might borrow from this technology.

Laser-doppler anemometry has been used for many years in both the laboratory and on production machines to study the flow characteristics of discharges from the headbox. While not measuring flocculation directly, the mean, and sometimes irregular flows can be measured by using the interference of two converging laser beams to create fringe patterns. Detectors measure scattered light from particles moving through the fringe pattern [136].

Measurement of table activity on Fourdrinier paper machines has been made by using a statistical photoclinometric technique. A stroboscope illuminates the forming fabric and a CCD camera captures the images. Photoclinometric methods relate the brightness variations in a single image to shapes. For this application, statistical parameters describing the surface in both vertical and horizontal directions are useful. The shadow method derives these parameters independently of the scattering laws by analyzing the detected distribution of shadows (compared to illuminated areas) on the surface. Measured surface properties are used to develop models for table activity and its effect on paper structure and ultimately formation [137].

Other investigators have emphasized the need for including table activity in any analysis of forming dynamics by developing an index for table activity with the use of the back-scattered signal from a laser. The index is incorporated with the MD profile of drainage and stock speed to determine the effect on paper structure [138].

A quantitative evaluation of forming hydrodynamics has been developed by the use of high speed digital imaging, computational image analysis and spectral analysis. Halogen lights illuminate the sheet and images are captured by a CCD camera system. The raw images are mathematically enhanced for capturing details of the forming jet, impingement, and forming dynamics along the forming table of a Fourdrinier machine. Detailed imaging can be used to obtain a qualitative level of surface turbulence in the jet in addition to mean flow structure [139].

The understanding and monitoring of flocculation has been studied by many investigators, usually in a laboratory setting. The quantitative evaluation of pulp flocculation usually proceeds in a similar fashion to that for formation by the use of light transmitted through or reflected/scattered from a sample under varying flow conditions [140]. Other investigators have studied filler flocculation by image analysis using a projected area criterion [141], while others have used scanning laser microscopy for microparticle flocculation, correlating performance with dynamic drainage jar readings [142]. The chemical/colloidal environment of course has a large effect on fiber flocculation and is an active area of investigation [143,144]. Methods for the measurement of the chemical/colloidal charge environment will be discussed in Chapter V.

E Smoothness and porosity

1 Introduction

With printability as the most important printing property, various methods have been employed in its evaluation. Smoothness (roughness), gloss and porosity (coating and substrate) measurements all give valuable information, but none correlate unambiguously with print quality [23]. The ultimate test for printability remains the proof test run. Gloss has been classified as a surface property [32], and will be discussed in Chapter IV. This section will concentrate on the measurement of smoothness and porosity with a brief mention of sheet temperature measurement devices.

2 Smoothness measurement methods

The laboratory-based air-leak methods for smoothness utilize the measurement of air flow rate between a flat surface of specified shape and a sheet of paper. While the geometries of such testers as Bekk, Bendtsen, Sheffield and Parker Print-Surf vary, correlations between them have been made so that specifications for paper using one test device can be satisfied with another [145].

Another name for smoothness measurement might be surface profilometry, usually accomplished with optical methods or mechanical stylus sensing. The "Laser Table" described by Lloyd et al. is a non-contact device that measures surface topography. It provided correlation with Sheffield roughness measured on whitetop linerboard [146]. Optical sensing of smoothness is intimately tied to fiber properties and light scattering characteristics. Recent investigations have attempted to discover the relationships between fiber dimensions, fiber fibrillation, relative bonded area, fines content and light scattering coefficient [147]. A method using frequency analysis has compared the traditional mechanical contact stylus smoothness measurement technique with optical sensing to evaluate precision and range. Good agreement was found at larger lateral dimensions, and, as might be expected, the optical method reported higher roughness for smoother samples than did the mechanical method [148].

3 On-line smoothness testers

On-line testers, now in the maturation or refinement stage of development, usually use the detection of near infrared laser light. One manufacturer measures the scattering effect of the surface of the paper, using an incident angle of 75°, the same as with gloss measurements, for a non-contacting smoothness measurement. A 6000 pixel CCD detector measures the distribution of the scattering, which allows development of physical models to describe the roughness of the paper surface. The influence of temperature on the measurement is minimized by integrating the laser light source, detector, mirrors and window into the same metal block which is temperature stabilized by water circulation. Smoothness measurements are translated into Parker Print Surface values [149].

Another manufacturer uses a laser profilometry method to measure surface contours in a non-contacting fashion, stabilizing the sheet with an air bearing. The PrecisionPLUSTM Surface Sensor focuses a 20 μ m spot of light from a laser diode normal to the paper surface and receiver optics view the spot at a 45° angle, as shown below in Figure 16. Note: This sensor has



Figure 16 The PrecisionPLUS[™] Surface Sensor. Redrawn from [150]. Courtesy of the Honeywell-Measurex Corporation.

been temporarily withdrawn (late 2000) from the market due to difficulties with the air bearing/vacuum ring used for sheet stabilization. The overall concept of the sensor is correctly shown in Figure 16.

A pair of silicon photodiode detectors is used to resolve sheet surface position by the difference in received signals. Sheet surface feature height is displayed in seven spatial bandwidths, representing surface features of 40 to 5440 μ m. A z-direction resolution of 0.1 μ m is claimed, a range of

100 μ m, at a profile display of 2 cm and a frequency response of 1 MHz. Measurements correlate to Emveco Micro Average and air-leak smoothness values [150].

4 Porosity measurement

The ratio of air volume (usually pore volume) in a sheet divided by total volume is called the porosity of the sheet. While a fundamentally important property, this is rarely measured in papers, except in laboratory studies. A related property, air permeability, is often determined, both in the laboratory and on-line. Air permeability is defined as that ability of a paper that allows air to flow through it under a pressure difference through the sheet. Air permeability is not a measure of porosity, and the two terms should not be used interchangeably, as is often done. In practice, the quantity that is measured is not the amount of air which passes through the sheet, but its inverse, the resistance to the passage of air, expressed in seconds [32].

An on-line device for measuring air permeability, the L&W Scanpro Porolog, utilizes a head which lightly presses against the running web, resulting in a measurement range of 10–200 Gurley seconds, 1133–56.6 Bendtsen units or 76.8–3.84 Coresta, corresponding to a permeance of 12.8–0.64 μ m/ Pa s. Air consumption is 50 l/min while measuring, for basis weights from 17–300 g/m² [151].

5 Sheet temperature

Sheet temperature measurements are sometimes necessary as compensation signals for moisture and other paper quality measurements. Measurement via infrared radiation from the sheet is used in a typical arrangement shown in Figure 17 below.

Radiation from the sheet impinges on the thermopile sensing element via a conical collector. Specifications quote an accuracy of 1 C, a repeatability of 0.2 C, a range from 0 to 260 C, and a response time of 250 ms [152]. This gauge will be, in the near future, replaced with a device manufactured by a third-party supplier at reduced cost and equivalent sensitivity and accuracy.

Neles Automation manufactures an IQWebTemp gauge that measures sheet temperature via IR radiation reflected by a moving web. The gauge has an integrated high intensity light source and detector in a single-sided head. An accuracy of 0.2 C and a repeatability of 0.1 C is claimed with a resolution of 10 mm [153].



Figure 17 The Measurex Sheet Temperature Sensor. Redrawn from [152]. Courtesy of the Honeywell-Measurex Corporation.

III MECHANICAL PROPERTIES

A Introduction

The ability to perform its intended function during use is one of the most important attributes of any paper product. One of the more significant properties crucial to this task is the strength of the paper, and nearly all enduse applications involve strength specifications of one kind or another. Unfortunately, this property is one that cannot be directly measured on-line, and can only be measured either indirectly on-line, or in the laboratory in a destructive fashion. Fortunately, sheet stiffness can be measured on-line, with strength and fiber alignment inferred from this measurement. Discussion will include both in-plane and z-direction measurement technology.

Break and defect (holes, streaks, marks) detection systems are included here since defects directly affect strength, and changes in sheet structure, reflected in on-line measurements, may be a precursor to sheet breaks. In addition, some mention will be made of certain miscellaneous mechanical measurements, and pulp properties as they may be predictive of paper properties.

B Strength and stiffness

- 1 The ultrasonic stiffness measurement
- a Contacting in-plane

Much of the exploratory work to develop a method and apparatus for measuring stiffness ultrasonically during the late 1970's and early 80's is attributed to Professor Kazys in Lithuania, and Messrs. Baum and Habeger at The Institute of Paper Chemistry in Appleton, WI. They recognized that the square of the velocity of sound measures stiffness per unit mass. If this is multiplied by the basis weight, the result is extensional stiffness (modulus times caliper) which correlates with tensile strength. The ratio of the extensional stiffnesses in the MD and CD is a measure of the sheet anisotropy, correlating well with stress-strain curves and fiber orientation measurements. This technique has applicability for both on-line and laboratory measurements [154,155,156].

The on-line ultrasonic device basically consists of an arrangement that rides on the sheet at the dry end of the machine. In one embodiment, a pulse train of sine waves is sent to a piezoelectric crystal in a transmitter wheel, creating a mechanical disturbance in the paper. Two receiver wheels separately detect the MD and CD disturbances, measuring longitudinal velocity in the MD and shear velocity in the CD. Unfortunately, the measured velocities are functions of temperature, moisture content, furnish composition and any machine operation that affects the sheet density (or elastic properties), and suitable compensation must be made [6,157]. Continued development over the years has allowed maturation of the technology, resulting in various physical arrangements and improvements in the generation, detection and processing of the signals [158,159].

The ultrasonic method facilitates measurement in several directions in the plane of the sheet to determine the orientation of the elastic properties. The results of the measurement are usually presented in a "polar plot," an idealized form of which is shown below in Figure 18.

There are several key properties of note that correlate to fiber orientation. The shape of the polar plot should correspond to the probability polar plot of fiber alignment. The TS_{MAX} and TS_{MIN} are the maximum and minimum tensile stiffnesses, respectively. The ratio of these two is the tensile ratio, or orientation index. TS_{MD} and TS_{CD} are, of course, the stiffnesses in the MD and CD. The angle that the line through the TS_{MAX} makes with the MD is called the polar angle α . Differences in α across the machine contribute to board twist and sheet curl. Analysis of the polar plot has enabled correlations to be made with the paper machine processing conditions of restraint drying,



Figure 18 An idealized fiber orientation polar plot.



Measurement cylinder

Figure 19 The ABB® Ultrasonic Specific Stiffness Sensor. Scanned from [163]. Courtesy of ABB, Inc.

headbox jet rush/drag, and sheet properties such as hygroexpansivity, burst and compression strength [160,161,162].

Commercial devices for on-line ultrasound based stiffness measurements exist either in a single-point format [163] or mounted on a scanner as depicted below in Figure 19. In this device, there are two sets (one for longitudinal, one for shear) of three ultrasonic transducers mounted in a cylinder that rolls on the moving paper web. Each transducer set consists of one transmitter and two receivers. When the three transducers in a measurement set come into contact with the sheet, the transmitter fires a short burst of 60-kHz ultrasound into the sheet. The sound wave travels in the plane of the sheet and is detected first by the near receiver, then later by the far receiver. Velocity is determined by the difference in signal arrival times and the path length difference between the near and far receivers. The entire measurement takes place inside of a 200 μ s time window [163].

b Out of plane

Laboratory-based traditional instrumental methods for measuring internal (z-direction) bond strength have been given the labels of dynamic (Scott), static (tensile), delamination (peel), cohesion (shear) and toughness (cantilever) [164,165]. Researchers at the Institute of Paper Science and Technology (IPST) in Atlanta, GA have developed an on-line device for z-direction elastic stiffness measurement, a depiction of which is shown below in Figure 20.

As shown in Figure 20, two piezoelectric ceramic transducers, an emitter and a receiver, are used to transmit (1-MHz single sine wave) and receive ultrasonic pulses, respectively. The transducers are mounted on the axles of rubber tires filled with a fluid. This arrangement ensures continuous acoustic coupling between the stationary transducers and the rotating wheels. Two ultrasonic pulses are collected: the directly transmitted pulse (pulse 1), and a reflection-delayed pulse (pulse 2). Time differences between these pulses obtained with and without paper in the nip are used to determine paper thickness, traveling time, and thus velocity through the paper. Special precautions are taken to ensure that the two pulses are free of spurious interference [166,167].

c Non-contacting

Still using ultrasound to detect both in-plane and z-direction elastic properties, other researchers have explored methods for producing and detecting sound (Lamb) waves in paper without contacting the sheet, by using lasers. An interferometric technique was used to detect motions of Lamb waves [168,169]. Originally used on fixed sheet samples, the technique continues to







Figure 21 The Honeywell-Measurex device for measuring elastic stiffness. Courtesy of the Honeywell-Measurex Corporation.

be investigated using a moving web simulator. Texture noise has been identified as a major problem to be circumvented [170].

2 The mechanical method

Another on-line method for strength measurement involves the elastic stretching of the sheet as it passes over a sensor assembly as shown below in Figure 21. The sensor is mounted on a scanning platform at the dry end of the paper machine. Above the sheet is a segmented contacting ring surrounding a sheet proximity sensor, while from below, a retractable spherical-segment wheel is loaded into the sheet. The CD curvature of the wheel matches the MD radius so that the same strain is created in both directions. The strain is measured relative to the segmented ring structure by a wheel position sensor in the upper unit. Vertical force transducers, located behind the MD and CD ring segments, measure the forces in the sheet, and convert the signals to MD and CD extensional stiffness. The sensor compensates for web tension and bending resistance of the web by measuring the forces at two different wheel positions [171].

Specifications include a repeatability of 1% and an accuracy of 6 to 12% for MD and CD extensional stiffness. A measurement range of 30 to 30,000 kN/m is quoted, for a spot diameter of 8.9 cm with a response time of <10 ms [172].

C Miscellaneous measurements

1 Web tension

The measurement of web tension can be an alleviating factor in solving sheet flutter and wrinkling problems caused by low tension, and sheet breaks because of high values. The traditional method for measuring web tension is to measure the load caused by the web on a roll. A large wrap is required, profiles cannot be measured, and load cells are sensitive to vibration and temperature changes. Other methods for tension measurement include: measuring the counterpressure of compressed air blown into the web, measuring a reaction force when the web is deflected, using a laser beam to measure the velocity of a propagating membrane wave in the web, and using the traditional method mentioned above but with a series of rolls with load cells to measure tension profile.

Another method is based on measuring the pressure of an air film between a curved surface and the deflected web at about 15° wrap. At high enough speeds (>500 m/min), an air film is formed between the surface and the web which holds the web away from the surface. The pressure of the air film

increases from ambient in the entry region, achieves a relatively constant value in the central region, then decreases to ambient at the exit. The magnitude of the pressure in the central region is the value of the web tension T divided by R, the radius of curvature of the surface. A tension profile is measured by locating pressure measurement orifices at various CD locations [173]. A measurement range of 0-1500 N/m is claimed, with 0.5% accuracy and 0.25 N/m resolution [174].

2 Layering

The production of a web whose fibers are different at various z-direction positions in the sheet can produce some interesting mechanical properties. While a structural characteristic, this technology is briefly discussed here because of the special mechanical niche it occupies. For many years, board and carton stock production has used the joining together of plies to form a composite sheet structure. By contrast, layering technology forms the total sheet in a simultaneous fashion with a divided-channel head-box, the process being referred to as "stratified forming." Layering was first employed on a production basis on a linerboard machine in Obbola, Sweden some 30 years ago, yet this author knows of no subsequent board machine installations.

The technology has been embraced by the "soft tissue" manufacturers, frequently coupling layering with blow-through drying in production machines dating from the late 1970's [175]. As a structural example, if flexible, relatively unbonded fibers are placed on the outside layers of a sheet, and have the strong, well bonded, long fibers in the middle, the result is a silky feeling, flexible, "soft" sheet with low bending stiffness, yet sufficient strength. In addition, if the anisotropy of the sheet is minimized, sheet drape is improved, as bending stiffness is more equal in all directions.

More recently, the office paper grades have become interested in layering as a means to achieve a more symmetric sheet, improve some critical properties, and reduce basis weight, albeit at the expense of a more complicated paper-making process [176].

Analysis of the z-direction fiber distribution has traditionally been done by tape stripping, fiber staining, microscopic examination, and counting – a laborious task [177]. Another method, considering the "soft" three-layer construction mentioned above, would utilize the flocculation differences between short and long fibers. This method is based on the measurement of the locations of fibrous segments in the serial cross-sections of the sheet [178]. A compilation of essentially all the known methods for analyzing the z-directional sheet structure has been reported by Niskanen [22].

3 Creping

Creping is a process that is important, and almost exclusive to, the tissue segment of the industry. For tissue production, the moist sheet is glued to a large diameter cast iron drum (Yankee), then scraped off, shortening the sheet by perhaps 15%. Stretch is thereby imparted, and MD flexibility enhanced.

The measurement of crepe quality is frequently done off-line by visual inspection or by the use of a mechanical or optical profilometer. One on-line method uses a He-Ne laser to record and quantify the creping structure by recording the wavelength and depth of the crepe as it is reflected (or backscattered) from the sheet. The device is in the shape of a curved skate that rides in contact with the underside of the sheet just after the creping blade [179,180].

D Defect measurements

1 Introduction

Defects in the sheet can range from minor imperfections to more major sheet irregularities that may result in reject production, or sheet breaks. Monitoring the condition of the total machine has proven useful in preventing and troubleshooting defects before, and as they occur. Accordingly this topic will receive some discussion, as will the technology of using various optical systems to monitor the machine and sheet. The identification and analysis of sheet marks, streaks, holes and cracks will receive attention, as will the possibility of coordinated control of many interactive physical properties, including their prediction from pulp properties.

2 Diagnostic methods

The diagnosis of process disturbances is necessary for the efficient operation of any process. When coupled with sheet defect analysis, disturbance diagnosis is a powerful tool in the arsenal of weapons used in the ultimate elimination of the cause(s) of the defect. Process problems can be grouped in many different ways, but one possible criterion is to use the time scale of the symptom, resulting in three classes of malfunctions. One class, slow performance degradation, might be caused by the wearing or fouling of equipment. Another class might be periodic fluctuations, with high frequency oscillations caused by rotating equipment, and low frequency variation which might be caused by upstream disturbances (discussed later). The third class might be called sporadic phenomena, perhaps caused by a sudden need because of a violation of a specified limit [181].

The major papermaking sensor system manufacturers (ABB, Honeywell-

Measurex, Neles Automation and others) all offer large machine-monitoring systems which provide many-faceted data logging and analysis capabilities that are necessary for isolating and identifying the culprit for any slow or periodic performance degradation [182]. Sometimes, however, there is a need to non-routinely measure velocities of various machine components to assist in trouble shooting. Recently developed laser-based devices are capable of measuring all moving object velocities with high accuracy. Jet-to-wire speeds can be verified, roll and fabric speeds can be measured, as can the exact paper length at the reel. One such device uses two laser beams that are projected onto the surface to be measured. The time difference between the two beams to measure the same spot is used to calculate speed [183].

For periodic fluctuations, time series analysis of mill data is particularly useful [184], but ultimately, one must look to the web itself. Off-line paper analyzers can identify variability in the MD and CD with powerful analysis tools, using sensors for basis weight, caliper, gloss, opacity, ash and printability, as can selected on-line systems [185].

An on-line commercial system is available for the measurement, analysis and reporting of random and periodic variations with subsequent defect sources being identified, separated and classified by using differences between disturbance patterns in the web. To distinguish one defect from another, the



Classification of Sheet Defects

Figure 22 Sheet defects categorized in terms of MD wavelength and CD width, with corresponding spectra. Courtesy of JH Instrumentation Ltd.

CD width and MD length of each type of variation must be measured. To do this, two or more optical devices (light source, lens, fiber optic light guides and diodes) capture light reflected from the web in a group of 1 mm diameter areas aligned at predefined intervals in the CD. Multiplexed outputs facilitate comparison of the reflectance of areas from 3 to 48 mm apart in the CD. Power spectra are computed and the results are reformatted so that they may be plotted as power per decade against the logarithm of the MD wavelength. As the distance between CD locations is increased, the width of defects contributing to the spectra increases, allowing defects to be categorized in terms of CD width and MD wavelength. A map of the MD and CD dimensions of some common web defects revealed by power spectra is shown below in Figure 22.

A typical spectrum, such as that shown on the vertical plane at the rear of the figure, relates to one or more separated defects as suggested on the floor of the plot, with accompanying causes as indicated [186].

3 Web inspection systems

Sheet inspection systems have been in wide use in the paper industry for 30 years. The exploratory development efforts of three decades ago utilizing brush detectors and ultraviolet systems has matured to systems using lasers, IR phototransistor technology, and charge-coupled-device (CCD) elements [187]. Laser systems use rotating mirrors to create a moving laser spot over the web in the CD, using reflected or transmitted light to identify defects [188]. IR phototransistor systems utilize a discrete source and photosensitive element to identify defects via rapid changes in transmitted light intensity. The CyberMetrics Edge Crack Detector is an example of a device that uses this technology [189]. Finally, CCD camera systems scan the electrical charges of the arrayed elements at kHz frequencies. Signals exceeding certain threshold levels are interpreted as defects. These systems are usually referred to as "full sheet" imaging systems, since an accurate representation of CD variation can be obtained, as well as a grayscale image of defects in the sheet [190].

Included in the category of web inspection is line-scan and full-frame IR imaging systems for visualizing temperatures in the papermaking process and thus diagnosing problems on the paper machine and in the sheet itself. The most recent developments in IR imagers use a focal plane array (FPA) of detectors, each of which is responsible for producing one point in the total IR image. For a more detailed discussion of IR imaging technology refer to the article by Charles [191].

4 Sheet break systems

Detecting that the sheet has broken is not particularly challenging, but determining the real cause of the break once it has occurred can be a difficult proposition, as is identifying those conditions that have the potential to cause a sheet break. Sheet break trouble shooting has been greatly enhanced in recent years by the use of video camera surveillance systems that monitor the sheet as it progresses down the paper machine. Routinely installed on paper machines for the past 20 years, systems now no longer use video cassette recorders, requiring the need to play back VCR tapes to find the source of the break. Video camera systems now offer the capability not only of instantly identifying when and where the sheet broke, but can also evaluate running conditions and alert the machine operator when conditions leading to a break are indicated. When networked with other process computer systems, these systems have the ability to evaluate a full spectrum of operating conditions at the time of the sheet break [192].

Camera technology has advanced rapidly to the point where resolutions of 300,000 pixels per image are available, with high sensitivities of <0.1 lux and fast shutter speeds of 1/10000 of a second. Systems are available where 60 seconds of video are digitally recorded at 60 frames per second in RAM memory so that one minute of machine running time is available for analysis. When a break occurs (detected by photocells or lasers), computer software can identify when and where the break originated by synchronizing camera frames with machine speed [193,182].

5 Sheet marking

Sheet marking refers to (usually) periodic variations in appearance caused by structural differences that are long in wavelength compared to fiber dimensions. Some marks can be characterized as wet-end barring, originating from pressure pulsations or fluid flow phenomena upstream of the forming fabric. These disturbances are usually studied by spectrum analysis of both equipment and the sheet [194]. Other marks that are perhaps more random might be streaks caused by secondary flows in the headbox. These can be identified by high resolution weight measurements [195] and holographic interferometry [196].

The most common method for periodic mark analysis involves the use of image analysis and 2-D fast Fourier transforms (FFT). Marks originating from either the forming fabric, suction rolls, or press fabric can be identified and separated from the stochastic variations of the paper surface by FFT filtering [197,198,199]. While this technology is presently an off-line

technique using reflected laser light, it has promise to someday translate to an on-line system.

6 Coordinated control and pulp properties

Paper properties are linked together in many ways. Any attempt to optimize one property will usually affect many others. Achieving uniformity on the machine is being greatly assisted with a variety of techniques which range from attempting to measure the characteristics of individual fibers to developing real-time expert systems for paper quality control, to off-line analyses of paper as diagnostic instruments [200].

The measurement of pulp fibers can be used as a quality-control feature of incoming raw material for paper production. Such devices might measure key quality indicators such as freeness, fiber length and shive size distribution [201], or fiber length and shape – the measurement of which can characterize how mechanical treatments in pulp processing change fiber curl, kink and length distributions [202]. Certain devices for fiber length and coarseness measurement have moved from the laboratory to on-line usage, with benefits ranging from furnish quality optimization to estimations of resultant paper strength [203]. The ultimate objectives are to be able to assure uniform furnish to the papermaker, and provide information concerning resultant paper property development [204,205].

By measuring fiber and pulp properties, paper machine runnability and certain properties can be predicted using a variety of statistical techniques [206,207]. The measurement techniques cover a wide range, including, but not restricted to, specific surface area, image analysis, confocal microscopy, and chemical analysis [208].

Once the stock has been sent to the machine, the problem changes from raw material quality control and prediction of properties to one of making the best use of what one has. Whether using neural networks with wet-end chemistry measurements to diagnose web breaks [209], using statistical correlations with various machine mechanical measurements for real time paper quality analysis [210], or using portable diagnostic instruments to trace problems to their source [211], the objective is to maximize and stabilize the performance of the entire pulp processing and papermaking system [212].

Coordination of property development is becoming more feasible with more powerful computer systems and the application of neural networks. As an example, CD uniformity is typically controlled by two or three different control stations on the paper machine. To attempt proper coordination, a supervisory control system was introduced to allow simultaneous on-line control of basis weight and fiber orientation on a fine paper machine [213].

As another example, paper curl can be a printer's nightmare, and frequently the measurement of curl must be postponed until the end of a reel turn-up. An on-line device exists for curl measurement consisting of a laser, line generator and digital camera [214], but a better method might be to predict, then control and eliminate curl before it develops by using neural networks [215]. By using modeling tools for the various nonlinear papermaking processes, and presenting parameters that characterize a current paper reel as inputs to a neural network, a prediction can be made regarding whether the resulting level of curl will be within specifications. In parallel, presenting these same data to another network forms a model for predicting the absolute level of curl. The two predictions can then be put in context for machine operator guidance by including not only acceptability indicators, but also regression models in which certain parameters can be altered to reduce curl [215].

IV APPEARANCE PROPERTIES

The appearance, or "optical" properties of paper are usually thought of as opacity, brightness, color and gloss [32]. Also included in this discussion will be the measurement of ash and coat weight, since the purpose of filler and coating is to enhance the sheet's appearance, usually for the purpose of printing. The reader who is interested in learning more about the measurement of the optical properties of paper should consult references [216,217].

A Ash

1 Measurement

An excellent review of the prior developments and state of the art of ash measurement in the early 1980's has been provided both by Pfeifer and Walbaum & Lisnyansky [1,2,3]. Methods in this exploratory phase of filler measurement including beta backscattering, X-ray backscattering and X-ray fluorescence were reviewed, but the preferred method at the time was X-ray absorption. Beta backscattering provided only weak sensitivity to filler, and X-ray backscattering was deemed to be too complex and error-prone. X-ray fluorescence for the determination of TiO₂ was quite feasible, but clay determination was judged not to be feasible due to the strong attenuation of low energy X-rays by air. In spite of this, SentrolTM developed the Poly-Ash Sensor that measured clay concentration by preferential absorption while TiO₂ and CaCO₃ were measured by X-ray fluorescence. The radioisotope gamma source was Fe-55 [218].

The most promising on-line methods cited 20 years ago have resulted in being those most frequently used in the commercial devices of today: X-ray absorption and fluorescence. Fundamental to the X-ray absorption measurement technique is the fact that the attenuation curves for clay and TiO_2 are so different (K-shell edge at 4.966 keV) in character. This allows rendering of the two attenuation coefficients to be effectively equal by shifting the output of the X-ray tube with anode voltage, resulting in composition insensitivity. Work over many decades to solve the stability problems of X-ray tubes for the stringent requirements of X-ray spectroscopy, along with specialized design of power circuitry has enabled maturation of this technique for ash measurement.

Some laboratory methods for ash determination deserve mention. Qualitative methods include scanning electron microscopy, thermogravimetric analysis and energy-dispersive X-ray analysis. X-ray diffraction can be used to identify the fiber and individual filler components in paper, since each has its own unique diffraction pattern, assuming each component has a crystallographic lattice. Unfortunately, the presence of more than one mineral species can complicate the process because of partial superposition of patterns, yet the speed of the test and its quantitative determination features render it a useful test [219].

X-ray fluorescence spectroscopy has matured to the point of being able to identify and precisely determine the amounts of several different common fillers in a variety of paper grades. In one laboratory procedure, the paper is dry pulverized, then formed into a pellet. The intensities of the individual elements are determined using K-alpha peaks, from which filler levels are derived. The exact concentrations of the fillers (clay, CaCO₃, TiO₂, talc, white mica, and sodium aluminosilicate) are established according to stoichiometric calculations [220].

2 The sensors

Commercial on-line ash sensors utilize X-ray absorption and/or X-ray fluorescence. An example of an absorption sensor is shown below in Figure 23. This sensor utilizes an X-ray tube, a krypton-filled ion chamber, and necessarily operates in conjunction with the basis weight and moisture sensors on a scanning assembly for measuring percentage ash. Total ash content is measured with a repeatability of 0.1%, an accuracy of 0.5%, with a 10 ms response time. A range of 0 to 35% ash is claimed for basis weights up to 450 g/m², with a spot size of 1.9 cm diameter [221]. Another manufacturer uses an Iron 55 radiation source, claiming better source stability. Similar specifications are quoted [222].



Figure 23 A Schematic of an X-Ray Absorption Ash Gauge. Redrawn from a Honeywell-Measurex Corporation brochure [221].

The IQAsh-C from Neles Automation operates on the principles of both X-ray absorption and fluorescence. Absorbed radiation is used to measure the total ash content with an ion chamber located on the opposite side of the sheet from the Fe-55 source. A solid state detector located with the source head measures the fluoresced energy coming from the sheet, independently determining the values for clay, TiO₂ and CaCO₃. This sensor's range is up to 40% clay and 20% TiO₂ or carbonate, with an accuracy of about 0.4% and a repeatability of about 0.3% for sheets <250 g/m² [223].

B Coat weight

An excellent review article of the several methods for on-line coat weight measurement was authored 10 years ago by W. C. Rutledge [224]. He argued that rapid-response coat weight measurement is a necessity to avoid large reject rolls of product, hence the need for on-line methods. One method Rutledge discussed does not use a coat weight sensor, but calculates the mass of coating per unit area by measuring coating flow (supply and return), percentage solids, web width and speed. All the rest of the methods discussed by Rutledge employ a sensor based on the use of radiation from various portions of the electromagnetic spectrum. At the time, all of these gauges were still in the exploratory/maturation stage of development, with no universal, well-accepted industry method.

The beta-ray backscatter method is useful for single-recipe coatings, but this method is not selective and the sensor must be recalibrated for different coating recipes. Beta-ray absorption is a good means for measuring mass, and it has been common industry practice to employ two beta-ray gauges, one on each side of the coater, for coat weight measurement. Two moisture gauges are also needed, to correct for the different moisture levels of the sheet. Unfortunately, because of variation in the basis weight of the rawstock, one needs to subtract the two weight readings for the same spot on the sheet. The time constant of the gauges has to be increased to accommodate this, which leads to large errors. A main shortcoming of beta-ray instruments is due to coat rate statistics. Coat weight control loops may be quite short, compared to sheet basis weight loops with their long dead times between headbox and weight measurement. X-ray, gamma ray, and IR techniques for measuring coat weight all have a huge advantage in count rate, giving a much more precise measurement by not requiring as much averaging.

X-ray fluorescence sensors can be tuned to the energy of the element in question and serve as a very selective measure of that element, which would have to be a known proportion of the total coat weight. This method works well with titanium, but other elements have very soft X-rays which requires minimizing the air path and lengthening the time constant of the gauge, precluding the use for profiling work. (It is more difficult to detect calcium fluorescence than titanium, but much easier than aluminum or magnesium.) Differential X-ray absorption can measure total coat weight for the three main coating components – clay, TiO₂ and CaCO₃. A source tube with a spectrum properly shaped with filters is necessary so that the absorption coefficients of all components are equal, but because this is not monoenergetic radiation, the Lambert-Beer absorption laws are not followed exactly. Calibration can be directly achieved however.

Differential gamma-ray absorption gauges have the feature that gammarays are absorbed four to five times as much by the common coating materials as by cellulose or water. Depending on the mineral, gamma rays do not have a much higher sensitivity ration (mineral vs. cellulose or water) compared to machine X-rays. However, the various coating components have different absorption coefficients, resulting in the need to calculate a composite coefficient as a function of the percentage composition in the coating. Since Fe-55 is typically used as a source, this monoenergetic radiation follows absorption laws exactly (to the extent that the primary interaction mode is photoelectric).

The major manufacturers of coat weight sensors all use the principle of IR reflection. Absorption bands are present in the infrared for most coating compounds, and an adhesive such as latex of a known proportion in the coating is typically used as an index of coat weight. These sensors measure coating and surface moisture by sensing the absorption of IR radiation by water, latex, clay, calcium carbonate and cellulose, with an arrangement of one manufacturer identical to that of Figure 10 [225]. One manufacturer uses a single detector, while another uses multiple detectors to compare the signals from as many as six wavelengths [226]. Typical specifications for these gauges are a measurement range up to 50 or 100 g/m² of coat weight with an accuracy of 0.25 to 1 g/m² and a repeatability of 0.1 g/m². Sensor response times are in the 2 to 15 ms range, with a spot size resolution of 1 to 2 cm.

One manufacturer is in the process of developing an on-line gel point device for measuring the immobilization point of the coating by using a combination of diffuse and specular reflection. Benefits claimed include the continuous control of drying rate, energy savings, and the minimization of mottle due to binder migration [227].

C Gloss

Paper gloss is a qualitative property that cannot be readily expressed in fundamental terms. It is related to luster, the selective reflection of light, and glare, the undesirable reflection of excessively bright light. Physically, gloss is the intensity ratio of specularly reflected light to incident light. Some investigators have concluded that to characterize the entire visual impression of gloss, haze and orange peel must be included with specular reflection [228]. Gloss strongly depends on the smoothness of paper since specular reflection occurs in the surface layer of paper. High gloss relates to coating technology. The choice of pigments and binders controls the behavior of the coating layer, with particle size and size distribution usually being more important than shape [22].

The surface topography of paper represents a feature of the paper which does not permit easy definition of the boundary between smoothness and gloss. Characterizations have been made to determine the relationships between topography and gloss – an admittedly complex subject [229]. A relatively rough paper certainly will have low gloss, but a relatively smooth paper might still have low gloss because of small-sized surface gradients. Tilted surface facets reflect light in different directions, and if these facets have a wide distribution, low gloss results. This micro roughness feature causes anisotropy in gloss measurements because light incident in the CD hits more tilted fiber edges than does light in the MD [230].

Laboratory gloss meters use either lamps or lasers for light sources, whereas on-line meters use halogen lamps or LEDs. Commercial devices from the large manufacturers all use the standard 75° incident angle and ensure that an almost perfect reflecting plane is achieved. For wet sheets which cannot be contacted, sheet motion causes movements of the reflecting plane and the direction of specular reflection changes. A device has been developed which uses an array of CCD elements to find the center of the image, tracking the point of maximum specular intensity as a gloss measurement [231]. A sketch of a typical commercial on-line gloss sensor is shown below in Figure 24.



Figure 24 The Measurex Digital Gloss Sensor 4208. Courtesy of the Honeywell-Measurex Corporation.

An LED light source is focussed on the sheet, then onto a silicon photodiode detector. The light is chopped at 570 Hz, a non-harmonic of all standard AC current, to eliminate interference from stray ambient light. A beam splitter divides the light into a measurement and reference beam to provide automatic correction for source variation. An internal standard tile is inserted into the measurement path to periodically check and standardize the performance of the unit [232]. Performance specifications for most commercial gauges include (in gloss units) an accuracy of about 1, a range of 1–100, a repeatability of 0.2, a resolution of 0.1 with a profile measurement of about 1 cm [233].

D Brightness

Since on-line gauges for measuring brightness are usually combined with the measurement of opacity, specific gauge details will be incorporated in the discussion on opacity in the next section. One on-line device exclusively for brightness measurement has been under development at Tasman Pulp and Paper Ltd., albeit for measuring pulp brightness via diffuse reflectivity. Reflectivity varies with the direction considered and also the direction of the incident light, so a standard measure is adopted in which the average value, taken over all possible directions of incident light, is determined for light reflected at right angles to the surface. One method of achieving this is with the use of an integrating sphere to illuminate the material uniformly in all directions [234].

Initially, the use of brightness in the paper industry was to characterize pulp bleaching operations. The instrument of a half-century ago was manufactured by the General Electric Co. and used a Wratten 49 gelatin brightness filter. Illumination was at a 45° angle and viewed perpendicularly. The definition of the spectral weighting function was the product of the relative power distribution of the lamp, the relative transmittance of the optics and the filter, and the relative responsivity of the detector. Wavelength was standardized at 457 nm. About 1960, two colored glass filters replaced the gelatin filter.

Today, ISO brightness (2470) is the standard, and derives from ISO 2469 of some years ago which specified the now obsolete Zeiss Elrepho reflectometer. That instrument used diffuse illumination and viewing was normal to the sample. Present instruments that conform to ISO requirements usually take the form of abridged spectrophotometers that compute brightness from spectral data. The computation requires proper definition of the weighting function for the integral quantity of brightness [235].

In addition to the problem of a proper weighting function, the use of fluorescent whitening agents (FWAs) coupled with the availability of dif-

ferent instruments introduces both conceptual difficulties and measurement complications in the reporting of brightness values. FWAs will influence the measurement of brightness differently with different instruments. What is needed is a standardization of the power distribution of the radiation that gives rise to this fluorescence, which means a specification of the ultraviolet (UV) content in the instrument's illumination. By selecting CIE (Commission Internationale d'Eclairage) illuminant C, the measurement of indoor whiteness will have well defined conditions compatible with brightness [236].

E Opacity

On-line opacity sensors measure the light transmission capacity of paper. Since the relationship between light transmission and opacity is nonlinear (the square of light transmission varies linearly with opacity), signal processing must be used to translate the detector's signal into opacity values [23]. All present commercial gauges measure opacity only from one side, but opacity can be different on different sides. This feature is thought to be attributed to the surface reflectivity both of the specimen and the backing, implying a breakdown of the Kubelka-Munk theory [237]. Gauges for opacity are sometimes combined with formation, color, brightness and whiteness measurements as part of a scanning system at the dry end of a paper machine.

One gauge used exclusively for opacity, the Honeywell-Measurex Model 2240, uses a tungsten-halogen source lamp with a tuning fork chopper to modulate the light. Claimed specifications include a repeatability of 0.1%, an accuracy of 0.5%, a measurement range from 70 to 100% opacity, a spot size of 1 cm and a response time of 10 ms. A moisture measurement is needed as a prerequisite [238].

Another opacity gauge combines formation, opacity and brightness – the OptiPakTM, as shown below in Figures 25a and 25b. This sensor first measures a 1 mm spot, then a 30 mm wide opacity window. The sensor calculates the RMS relative optical density from these measurements to determine a formation index. Opacity is measured in the usual manner with transmitted light, and is claimed to be independent of sheet composition and brightness effects. Finally, the sensor measures brightness by reflected light with compensation provided by the opacity measurement. This gauge has a quoted opacity accuracy of 0.4 units and a resolution of 0.3 units with a range from 60 to 100% opacity [114].



Figure 25a The Source/Brightness side of the OptiPak[™]. Courtesy of ABB, Inc.



Figure 25b The Opacity/Detector side of the OptiPak[™]. Courtesy of ABB, Inc.

F Color

1 Background

The measurement of color and its control is certainly of paramount interest to certain segments of the paper industry. Not only is the accurate sensing of color important, but the data gained from its measurement, when trying to apply it to a color control scheme, has consumed considerable amounts of time and energy. The Hunter L.a.b. scales devised in 1958 were derived from the 1931 CIE Standard Observer used for determining the tristimulus values X, Y, Z. It is interesting to note that the XYZ system has its roots in Newton's experiments with light in the early 1700's and Grassman's work of 1853 [239].

Color matching with different color scales is of course a concern, as is the changing of color standards and the effect of fluorescent whitening agents on measurement, since these agents exhibit strong illuminator metamerism [240,241,242]. Thus the development of on-line color sensors and closed-loop control schemes has been hampered somewhat by confusion over standards and illumination. One of the first closed-loop systems to monitor shade values continuously and automatically correct variations was installed in the mid-1980's [243]. Development continued in this period by the use of spectrophotometers and mathematical models for control of colored and shaded white paper [244]. It then became possible to control color through the calibration of dye rather than the calibration of color [245].

The modeling of the coloration system on the paper machine, with the inclusion of multivariable control strategies has been implemented as a continuing development into the 1990's [246]. Unfortunately, for today's highwhite paper coloring, variants on the traditional Kubelka-Munk model are claimed to be inadequate, and a direct total radiance factor based model may be a better choice. The discrepancy between on-line gauges which measure a single layer of a moving sheet versus laboratory gauges which use an opaque stack of stationary sheets may never be uniformly resolved, especially when fluorescence is present [247]. Nonetheless, development continues, with novel opportunities for color measurement using spectrographic techniques with monochrome CCD cameras being investigated in the laboratory [248], and on-line measurement of the winding reel being studied on an operating paper machine [249].

2 The sensors

The color sensors from the three major manufacturers typically are intended to be used on a scanner platform, usually at the dry end of the paper machine. All use xenon flash-tube technology, 45/0 geometry, a variety of illuminants, and spectrophotometric techniques with a dual-head arrangement to achieve color measurement along with opacity and brightness. Opacity measurement is accomplished using (but not always) a tungsten lamp and any opacity change provides a compensating adjustment to the color measurement. Typical specifications include a wavelength range of 350 to 750 nm, a color calculation every 5 nm, color accuracy of 0.4 and repeatability of 0.1 unit CIE L.a.b. Reflectance specifications include a range of 0 to 200% and a reflectance resolution of 0.01%.

The Neles Automation IQColor sensor, Model A416039, directs xenonflashed UV light 5 times/sec through a filter which simulates the daylight spectrum conditions into a light guide. The light guide carries the light onto an optical ring that provides circumferential illumination. Reflected light from the sheet is transmitted through a second fiber optic light guide to a linear variable filter/array detector assembly. No gratings or prisms are used. One head (the detector) contains the flash tube, light conveying equipment and detector, while the other head contains the backing and calibration tiles, along with the light source for opacity measurement [250].

One head of the AccuRay[®] Smart Color Sensor contains the Smart Backing Tile Module, and the opposite head consists of a measurement module, shown below in Figure 26. In the Measurement Module, light from the flash tube is focussed by a toroidal mirror onto the sheet. The diffusely reflected light is focussed into a fiber optic bundle, traveling to an analyzer. The analyzer contains a holographic diffraction grating, dispersing the light into varying wavelengths for projection onto a photodiode array. The reflected energy is measured at each wavelength in increments of less than two nanometers for the calculation of color. The xenon flash tube emits UV energy to excite FWA's that may be present in the sheet. With the use of a software-controlled UV filter, brightness is measured with and without UV illumination to decouple the effects of FWA's and set alarm levels for brightening tolerances.

The Smart Backing Tile Module uses a six-tile carousel to automate sensor calibration, standardization and check sample routines. This head also contains the Autofocus Module which enables on-line color readings to be continuously adjusted for changes in the measurement focal plane. This module utilizes a high-velocity air stream to stabilize the sheet passline without contact [251].

The Precision Color Sensor, Model 4215, from Honeywell-Measurex, shown below in Figure 27, uses a quartz-tungsten-halogen (QTH) lamp as the primary source in the head on one side of the sheet. This is mated with a dichroic color balance filter to provide continuous illumination with an



Figure 26 The AccuRay® Smart Color Measurement Module. Redrawn from an ABB, Inc. brochure [251].

energy spectrum matching the visible portion of CIE Standard Illuminants C and D65.

The second source is a xenon tube, pulsed at 50 Hz, with a 420 nm lowpass filter to provide intermittent UV energy for measurement of the effects of FWA's. A beam splitter merges the two sources, creating a beam that alternates low-UV and UV enriched daylight illumination. A conical mirror spreads the beam within a ring of 24 planar mirrors to create a 360° illumination at an incident angle of 45°. Two fiber optic bundles collect reflected light normal to the plane of the sheet and direct it to a dedicated spectrophotometer. One fiber optic bundle views a black-backed portion of the sheet, while the other bundle views a white-backed portion of the sheet for an "infinite pad" opacity-insensitive measurement. A holographic diffraction grating in each spectrophotometer disperses the light into a continuous spectrum and reflects it onto a photodiode array detector from which computations based on improved Kubelka-Munk models are made. The head on the other side of the sheet contains the backing/standardization wheel with the standard tiles, and a noncontacting air vortex sheet stabilizer to maintain the sheet in close proximity to the backing wheel [252].



Figure 27 The Precision Color Sensor, Model 4215. Redrawn from a Honeywell-Measurex Corporation brochure [252].

V WET END CONTROL, CONSISTENCY AND CHEMISTRY

One of the most important factors in the production of paper is achieving uniformity of product, not only in the CD, but also the MD. Short-term property variation usually arises from on-machine causes while processing stock flow. These variations, and the systems for detecting and analyzing them were discussed earlier. Longer term variations tend to be only in the MD, and arise from three areas: upstream pulp manufacture, stock preparation operations, and on-machine water system changes. Since upstream pulp variability was discussed earlier in Chapter III, this chapter is devoted to examining the other two facets of potential long term variation.

The retention of ash and other fine particles has received much recent attention. This chapter will focus on those sensors and schemes that are used close to the paper machine for pulp drainage measurement and consistency monitoring as part of a retention control scheme. In section C of this chapter, "Wet End Chemistry," the gauges and schemes for monitoring the condition of electrical charge in the water system of the machine will be discussed. Since on-line charge measurement, coupled with consistency monitoring of the paper machine's white water system has provided new opportunities for optimizing retention-aid and wet end chemistry control, several commercial arrangements for wet end control will be presented here.

A Freeness and drainage

The use of the freeness (or slowness) drainage test is ingrained in our industry, with automatic testers having been developed over a half-century ago. It was realized quite early that the testers were sensitive to sampling, temperature and consistency, and some still are. The test itself, in spite of being empirical, is used to measure pulp treatment and to predict paper quality [253].

Researchers over the past three decades have been searching continuously for ways to improve the reliability and significance of the test and testers. In 1983, Brewster reviewed several on-line testers, categorizing them as either continuous filtration, batch filtration or batch permeation. He discussed their sensitivity to temperature and consistency, and correlation to CSF and TAPPI drainage time [254]. Another review was published in 1999 by Hojjatie and Coffin that similarly compared the performance characteristics and operating principles of five different on-line sensors [255]. These devices are in the refinement stage of their development, having moved from a purely empirical test to one which characterizes pulp and predicts forming response.

One laboratory type of drainage tester measures the change in the constant flow rate vacuum applied to a furnish as it drains on a screen. This device, essentially a modified Britt Jar, can be fitted with a microprocessor to control the time of dosage of chemicals and stirring regimen, in order to provide a drainage curve that is a good predictor of the forming performance of the furnish [256,257]. Another sensor monitors the drainage rate from a column based on ultrasonic techniques. The specific surface area of the pulp can be obtained by using a filtration model and the drainage data [258]. Finally, another laboratory instrument, called the pulsed drainage device, operates by promoting pad consolidation via thickening rather than filtration. It is claimed that this device has been validated by correctly simulating the onmachine response of different drainage chemistries in three newsprint mills [259].

A commercial on-line dewatering measuring device, the Dewatering Rate Analyzer, shown below in Figure 28, is being marketed as a device which monitors the chemical efficiency at the wet end.

This instrument automatically uses the Schopper-Riegler principle, measuring the time required for the water associated with the pulp suspension to pass through a screen, replicating the fabric function on a paper machine. In operation, a sample, typically from the headbox recirculation line, fills a chamber. A valve then opens which permits drainage through the screen and the forming pulp pad at the bottom. Drainage time is measured with a dual electrode, after which a cleaning cycle is initiated. Measurements are provided every 1.5 minutes [260,261].

B Consistency measurement

This measurement, unique to the pulp and paper industry, is perhaps the single most important one (together with flow), and is usually identified as





the one producing the most frequent headaches for the practicing papermaker. Portions of a number of literature sources are devoted to the discussion of consistency measurement and control [17,21,23], whereas other sources are devoted exclusively to this topic [12,262,263,264,265]. The primary focus of this section will be on the measurement of consistency in the paper machine water system and the consequent retention control strategies and systems. Some mention will be made of thick-stock measurement for the sake of completeness.

1 Thick stock measurement

The first continuous consistency sensor was the Källe type K9 of 1931 [262]. Forty years ago, consistency was considered to be a mature measurement, almost totally relying on mechanical devices for shear force measurements in the 2-5% range. It was well known that these devices were sensitive to pulp freeness, flow rate, temperature and pulp type. Today, we still rely on mechanical shear force measurements, but in addition we have light scattering, light transmission, nuclear radiation, radio waves and microwaves. It appears that we have returned to the exploratory/maturation stage of development.

Mechanical measurement devices might be categorized as either static (a fixed probe or blade) or moving (blades, rotating disks or propeller). One of the latest transmitters has the appearance of two blades on a rotating disk. It is claimed to measure torque and consistency on an absolute basis by operating on the pulp while in plug flow [266].

The development of high-intensity light-emitting diodes twenty-five years ago allowed further development of optical consistency sensors. These gauges relied on scattered or transmitted light for measurement up to 4% consistency. Most of these mechanical and optical devices are well documented in the literature and will not be discussed here [12,267].

Several other approaches to consistency measurement have been attempted with varying degrees of success. A radio-wave/dielectric constant measurement technique, now abandoned, was developed at the U.S. National Bureau of Standards in the mid-1980's [268]. Gamma attenuation devices measure consistency on the basis of density changes. Recent developments in plastic scintillation detector technology have improved sensitivity and stability [269]. Because the density difference between fibers and water is very small, high sensitivity is a must. Unfortunately, fillers are quite dense, and if present in the pulp, will yield a false high reading. Similarly, the presence of air will yield false low readings [262].

Microwave measurement techniques offer the promise of being independent of pulp type, fiber length, brightness, color and flow rate. The most prevalent commercial technique is the measurement of propagation velocity, or time of flight through the stock, which is a function of the relative permittivity of the material. Because of the factor of 10 difference in the dielectric constant of water and wood fiber, velocity is a strong function of consistency. These microwave devices measure both fiber and filler, and compensation must be made for the filler amount and type. In addition, this method is sensitive to air, conductivity and temperature, for which compensation must be made. One commercial device quotes specifications of a measuring range up to 8% C, with a sensitivity and accuracy of 0.0005% C at a flow velocity in the range of 0.3 to 5 m/s [270]. A similar microwave propagation technique uses the phase difference between an original wave and one which passed through the stock to determine consistency. This device is claimed to be resistant to the effects of contamination and bubbles, with a range of 1-10%consistency [271].

Another microwave technique under development is called Guided Microwave Spectrometry. This technique computes complex permittivity, comprised of dielectric constant, conductivity and molecular relaxation time. Temperature measurement is also used to further diagnose the makeup of the pulp [272].

2 Headbox and white water measurements – retention control

a SENSORS IN GENERAL

The range of these measurements is generally 1% and below. Accordingly, optical devices, either in transmission or scatter mode, are the sensors of choice, relying on the fiber's interaction with light, as shown below in Figure 29 for three types of sensors.

Sensor A uses linearly-polarized light from either a halogen bulb or a semiconductor laser which is passed through the measurement cell. The transmitted light is split into two beams, one passing through a second transverse-plane polarizing filter, the other passing through a third in-plane polarizing filter. The beams are detected by photodiodes and combined to produce a relative depolarization signal, which is a function of the total fiber and filler. The signal is insensitive to brightness, color, freeness or soluble additives.

Sensor B is based on the transmittance of light as being a function of consistency. Unfortunately, this sensor is relatively sensitive to changes in freeness and color, exhibiting non-linear behavior with changes in filler and dissolved solids.


Figure 29 A variety of optical sensors.

Sensor C uses forward and back-scattered light to produce a signal combined from the several detectors that is proportional to consistency. This type of sensor can be used at much higher consistencies, and in general its sensitivity to variations in the content of non-fibrous substance lies between that of sensors A and B. The exception to this rule is filler, for which this sensor is the most sensitive [12].

b Commercial sensors for retention management

To manage retention on a paper machine, the traditional approach has been to use first pass retention – a delayed quotient of two consistency values. Instead of retention, the total consistency of white water has been found to offer a better choice, since this stream carries the majority of poorly retained pulp components [273].

Several manufacturers have been active in producing low consistency optical devices that are incorporated into retention control schemes for the wet end of the paper machine. In general these devices measure consistency at the headbox and in the white water early and late in the forming zone. One such device, the kajaaniRM-200 C, is illustrated below in Figure 30.

This device is similar to sensor A in Figure 29, in that a polarized light beam is directed through a galss capillary cell, where the sample continuously flows. The transmitted light is directed through a special aperature disk for



Figure 30 Measurement principle of the kajaaniRM-200 C for woodfree pulp. Courtesy of Neles Automation.

scattering measurements, then through a second polarizer which splits the light into cross-polarized and parallel-polarized components that are detected by photodiodes. The depolarization signal mainly indicates the total consistency of the sample, and the attenuation of light is affected by the total consistency and filler consistency. Attenuation is strongly affected by scattering and light absorption. Since backscattering and attenuation are influenced by small particles, filler consistency is calculated from these signals [274].

For pulp containing a considerable amount of mechanical fibers, and thus a large fraction of lignin, the depolarization scheme loses effectiveness. Another sensor has been developed that uses two light sources and a combination of optical measurement principles including depolarization, absorption and scattering at several wavelengths from the UV to the near IR. An outline of this sensor is shown below in Figure 31.

The near IR semi-conductor laser light is polarized, passed through the cell, then is depolarized as before in Figure 30. UV light from the xenon lamp is directed through the cell via a filter and polarizing prism. The forward scattered light is directed through the lens and aperature disk to photodiodes. Backward scattering is also measured for both the UV and IR light by detection with a photodiode before the cell. Light extinction, as well as back and forward scattering, are measured at several different wavelengths. The signals are processed to monitor total solids and filler consistencies and floculation in the sample [23,275]. Use of the kajaaniRMi series devices in paper machine retention control schemes will be considered later in Section C: Wet End Chemistry.

Figure 32 below shows the components of a system with a different sensing scheme, similar to sensor A in Figure 29. Figure 33 shows a typical signal



Figure 31 The kajaaniRmi for wood-containing pulp. Courtesy of Neles Automation.



Figure 32 The BTG Wet-end Consistency Analyzer. Courtesy of BTG Pulp and Paper Technology AB.

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Figure 33 A sample signal trace from the BTG Wet-end Consistency Analyzer. Redrawn from [262]. Courtesy of BTG Pulp and Paper Technology AB.

trace. A light beam is directed at the suspension and a photo detector senses the transmitted light. Three independent filters process the detector signal. The first filter determines the mean value V_{DC} of the transmitted light; the second determines the peak value V_P ; the third filter extracts the AC component V_{AC} of the signal [276].

The "Peak Method" used in the analysis assumes that the suspension is substantially characterized by large and small particles. The large particles (fibers) form a relatively transparent network within which the much greater number of smaller particles (fillers and fines) float freely. Observation of a typical suspension over time reveals that the great number of small particles is relatively constant, whereas the number of large particles is few and variable. The average value of the transmitted light determines $V_{\rm DC}$.

Deviations from this mean value are mainly due to the large particles passing through the light beam. The highest light intensity and V_P occurs when no fibers are passing through the beam and the light is being dimmed only by the suspended fine particles. Thus the respective amounts of large and small particles in the suspension can be determined by the mean and peak values [277].

Referring to Figure 33, V_{CW} is the detector signal for clear water, and is used as a reference value. The AC signal, V_{AC} is plotted along with V_{CW} , V_P and V_{DC} . The large particle content (LPC) is the difference between V_P and V_{DC} , while the fine particle content (FPC) is the difference between V_{CW} and V_{P} . The total consistency is obtained by summing LPC and FPC. In addition, the FPC signal is further analyzed for the determination of ash content [276].

A retention control scheme developed by BTG using the De-watering Rate Analyzer from Figure 28 and the Wet-end Consistency Analyzer from Figure 32 is shown below in Figures 34a and 34b.

As shown in Figure 34a for the overall retention system, dewatering rate is measured on the headbox recirculation line and consistency is measured at the headbox, headbox dilution water, and top and bottom forming fabric white water flows.

In a bit more detail, Figure 34b shows how the signal for white water consistency CsT is combined with thick stock flow FT and consistency CsT information in a central processing unit which determines the set point of the retention aid flow controller RA/FIC. The basic concept regarding closed loop control on the retention aid is to stabilize the papermaking process by



WCA = Wet-end Consistency Analyzer

Figure 34a The BTG Retention System. Courtesy of BTG Pulp and Paper Technology AB.



Figure 34b Instrumentation for the BTG retention scheme. Courtesy of BTG Pulp and Paper Technology AB.

regulating the white water consistency WW/KIC with a remote set point [260,278]. Other schemes for retention control that use charge measurements will be discussed later.

Another manufacturer uses a scheme similar to sensor A in Figure 29 as an "on-line water quality measurement." Labeled a particle counter, the CHEMTRAC Model PM 2500 uses a technique called Dynamic Light Obscuration (DLO^{TM}) similar to the "Peak Method" discussed above. In reality, this device is a total suspended solids consistency sensor. The sensor uses an IR light-emitting diode as a source, detecting transmitted light with a photodetector. The transmitted light intensity is broken into two components. The DC component corresponds to the mean number of particles. The AC component corresponds to the standard deviation of the signal. With the assumption that the number of particles in the sample follow a Poisson statistical distribution, the RMS value of the AC component depends on the square root of the particle concentration [279].

c A laboratory device

A high speed retention tester for twin wire two-sided drainage and formation evaluation has been developed at the Laboratory of Paper Technology, Lappeenranta University of Technology, Finland. The tester utilizes a swinging headbox passing through a converging forming fabric zone in a time comparable to a modern twin wire former operating at 1600 m/min, with a pulsation frequency of about 200 Hz. Drainage at various positions in the twin-wire forming zone is captured and analyzed [280].

C Wet end chemistry

1 Introduction

The subject of wet end chemistry measurement and control was in its infancy some 25 years ago. It was viewed as a curiosity – a field of endeavor so complex that we had neither the ability to understand, nor control its behavior. This viewpoint was supported by the fact that a papermaking system has multiple, sometimes uncontrolled inputs and feedback loops that affect wet end chemistry phenomena. Compounding this is the fact that most wet end chemistry reactions are irreversible and time dependent, with interfering and interacting mechanical factors to be taken into account. In addition, there are frequently simultaneous competing aggregation and dispersion chemistries, along with very limited on-line data [281].

In many ways, the development of wet end chemistry control was forced by other advancements, such as high speed papermaking, hydraulic headboxes, twin wire forming, white water system closure, recycled fiber use, and perhaps most important, the switch from acid to alkaline papermaking. These developments made it clear to the papermaker that control of the chemical processes in papermaking was necessary. With the increased awareness of wet end chemistry came increased activity by instrumentation and process control companies in the development of applicable on-line sensors. For the reader interested in an in-depth discussion of wet end chemistry, a number of sources are available [281,282,283,284,285,286,287].

2 Just what are we measuring?

In 1983, the Retention and Drainage Subcommittee of the TAPPI Papermaking Additives Committee sent a questionnaire to all committee members. The questionnaire was also distributed to all participants at the 1983 Retention and Drainage, and Sizing Short Courses. Both papermakers and suppliers were asked what wet-end chemistry measurements were made in mills, and, if the staffing and instrumentation were available, what additional measurements would be made.

By far the most common on-line measurement was pH, with additive flow rates and consistency next [288]. The survey also indicated that there was a

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strong need for developing on-line methods for measuring charge and retention, since the total number of votes for these measurements was $2\frac{1}{2}$ times the number cast for the second place finisher, process stream solids/ash/fines levels. Next in line were measurements for dissolved inorganics, then freeness, drainage and first pass retention [289].

The instrumentation suppliers have responded. On-line instruments are now available for many of those measurements that were determined to be needed 15 years ago. The sensors for the measurement of freeness, drainage and consistency, along with a sketch of a retention control scheme has been discussed earlier in this chapter. This section, then, will be devoted to the examination of the state of the art for on-line sensing of charge at the wet end of the paper machine and its applicability in process control schemes. The design of appropriate mathematical models for describing these complex wetend systems will not be discussed, nor will the suitable control algorithms that might be applicable.

3 Electrokinetics and dissolved charge measurements – a tutorial

Electrokinetics refers to situations describing the slip plane within the electrical double layer. The zeta potential is defined as the potential at this plane, within which counterions bound to the particle move with the particle, and outside of which the counterions are free to move. Because discrete particles are involved, we are concerned with surface charge.

The electrostatic charge associated with dissolved polyelectrolyte additives (retention aids, wet/dry strength resins) is different in character than that with particles, since there is no surface. Thus the concept of zeta potential has no meaning with respect to dissolved charge, since there is no interface between the polyelectrolyte and the surrounding medium, and no electrical double layer.

The charge on colloidal particles plays a major role in the stability of their dispersions. Papermaking phenomena that are affected include pigment slurry preparation and the retention of fines, fillers, additives and size. The adsorption of polyelectrolyte dry and wet strength additives, retention aids and dyes is strongly influenced by dissolved charge [290].

a Zeta potential

The three traditional electrokinetic methods used for measuring zeta potential are microelectrophoresis, streaming potential and AC streaming current. AC streaming current has also been widely used for end-point determination for dissolved charge measurements, to be discussed later. In microelectrophoresis, the particle dispersion is placed in a cell as shown below in Figure 35. An electric potential is applied between the electrodes and the migration velocity of the charged particles is measured, resulting in a determination of electrophoretic mobility (μ m/s/V/cm). For particles >1 μ m in size and conductivities typical of those found in normal paper-making applications, the zeta potential is then calculated from mobility by a form of the Helmholtz-Smoulochowski Equation incorporating the fluid's viscosity and dielectric constant. Unfortunately, measurements cannot be made on papermaking fibers, but only fines.

For the measurement of streaming potential, stock containing all furnish components is forced through a screen, forming a porous plug as shown below in Figure 36. As the fluid passes through the plug, charges in the mobile part of the electrical double layer are carried in the direction of flow, creating a streaming current. This accumulation of charge creates an electric field, which then induces an induction current, equal and opposite to the streaming current. When the two currents achieve steady state, the resulting potential difference between the electrodes (the streaming potential) is measured. The zeta potential is calculated from the measured streaming potential, pressure drop across the pad, and the physical/electrical properties of the liquid. Unfortunately, laminar flow must be assumed and achieving a pad with a uniform and repeatable pore size is difficult [291].

Rather than a packed plug of the furnish, the AC streaming current measurement is conducted through a thin passage. In one version, as shown in Figure 37, a reciprocating piston forces liquid back and forth through the



Figure 35 A microelectrophoresis cell.



Figure 36 A streaming potential cell.

clearance between the piston and cylinder. Particles in the suspension become attached to the piston and the cylinder wall, but ions which are loosely held to the surface of these particles are hydraulically sheared. This ion motion produces the "streaming current" that is detected by electrodes in the sides of the cylinder. In practice, what is often measured is a streaming potential, not a current as the name suggests. In spite of this, certain manufacturers calculate



Figure 37 An AC streaming current detector (SCD).

electrophoretic mobility from the streaming current, fluid viscosity, and mechanical/motion parameters of the cell. More about this later.

Unfortunately, the streaming current measurement does not necessarily indicate the exact zeta potential of the particles, but rather whether a system is cationic or anionic. Fortunately, the isoelectric point of a suspension correlates with the charge reversal point on the piston and cylinder surfaces when polyelectrolytes are used to change the charge. Consequently, streaming current measurements have been widely adopted as end-point indicators in cationic demand determinations [281]. This leads us to the next section on dissolved charge.

- b DISSOLVED CHARGE
- 1) A few definitions

Dissolved, or soluble charge refers to the charge groups associated with dissolved polyelectrolytes in papermaking systems. Since there is no surface, there is no electrical double layer. *Total* charge is the sum of the dissolved charge, plus the quantity of charged functional groups associated with particles in a sample. *Cationic or anionic demand (or charge demand)* is the specific capacity of a test specimen to neutralize cationic or anionic titrants. The *colloid titration ratio* is the ratio of the anionic demand to the cationic demand of a sample.

2) And some explanations

Dissolved charge achieved high interest about 30 years ago when environmental pressures forced papermakers to increase water reuse. This practice resulted in increased amounts of dissolved and suspended colloidal solids in mill water systems. Many of these substances carried anionic charges, reacting with cationic additives, not only reducing their effectiveness, but also the effectiveness of many other chemical additives. These recycled anionic materials were thus given the name "anionic trash" or "interfering substances."

It became apparent that a method was needed to measure the amount of these interfering substances and predict their effect on cationic additives. Even though different approaches have been developed, most commercial methods are based on colloid titration. This procedure involves titrating a sample with a standard polymer that will react with its oppositely charged counterpart in the sample to form a one-to-one charge complex. The amount of titrant charge added up to the isoelectric end point equals the amount of oppositely charged, dissolved charge in the sample. The result of the titration is expressed as the amount of charge per unit weight or unit volume of the sample [292].

As an example of the effect of cationic demand, assume we have a cationic polymer which increases first pass retention (FPR). With a highly recycled water system, a certain extra amount of polymer, "the cationic demand" of the system, would have to be added before any change in FPR would take place, compared to the amount required with the "cleaner" water system.

Thus charge demand, whether cationic (usually) or anionic is an extensive variable that is volume dependent. Zeta potential is an intensive measurement and is not a function of sample size. Thus it is possible to have low zeta potential, yet high charge demand. While zeta potential measurements are useful as an indicator of stability, more often in papermaking we are concerned with charge demand measurements to achieve control.

3) The measurements

For dissolved cationic demand, a common procedure involves direct titration to the end point, as previously mentioned. A less common procedure, back titration, involves adding an excess quantity of a standard cationic polymer to the sample, then the remaining unreacted cationic polymer is neutralized by titration with a standard anionic polymer. The dissolved cationic demand may then be computed. To determine anionic demand, one would directly titrate with an anionic polymer. Another method for cationic demand would be the measurement of total organic carbon (TOC). This would truly determine the dissolved organic content.

There are multiple methods for end point determination. One method requires the detection of a dye color change when titrating. This procedure can be especially troublesome in the presence of paper mill dyes, and this difficulty led to a search for other methods about 20 years ago. One approach combines microelectrophoresis with colloid titration by titrating to zero zeta potential (or mobility). More recently, it has become common to employ an AC streaming current detector zero point reading as the endpoint in colloid titration measurements.

Total charge can be measured by titration without filtering out the solids, but not without some serious drawbacks regarding the application of colloid titration to particles. One of these is that a one-to-one charge reaction may not occur between the standard polymer and the particle surface. Another problem is that an indistinct endpoint frequently occurs when using either the SCD (in the presence of porous particles) or a dye indicator, making the endpoint determination very difficult.

c Challenges and Cautions

On-line charge and streaming potential measurements with properly calibrated instruments have been found to be of great assistance to the papermaker [293]. Reducing the electrokinetic variability of the furnish, thus improving stability, has been found to increase machine runnability [294,295,296]. Zeta potential and cationic demand at various chemical and pulp stream addition points has yielded valuable information regarding optimum doses of dispersants, dyes and polymers for better machine control [297,298]. But the cationic demand measurement is not without its concerns, in that many substances besides dissolved polyelectrolytes will react with the titrant: fatty acids, surfactants and colloidal anionics such as lignin. Because colloidal titration and zeta potential measurement are two different methodologies, they should not be expected to share any correlation [299,300]. Even the highly-regarded zeta potential measurement is susceptible to errors arising from changes in the conductivity of the pulp suspension [301]. The piston-type streaming current detector might be labeled as having a dubious theoretical basis [302] and high concerns with regard to cleanliness fatigue. Finally, the pad-forming streaming potential sensor is based on the Helmholtz-Smoulochowski (HS) Equation, deduced for a single straight capillary and not a bed of fibers. In view of the concerns about pad compressibility and fiber surface conductance, the HS equation is of unlikely validity [303].

4 Several sensors and strategies

Sensors for measuring charge demand and the retention control schemes that incorporate these sensors with consistency measurements will be the subject of this section. Sensors for measuring consistency were discussed earlier, along with one retention control scheme that did not use charge measurements. No attempt will be made to evaluate the performance of any system in comparison to another. Manufacturers are presented in alphabetical order.

a Chemtrac®

The Chemtrac® Electrokinetic Charge Titrator (ECT) measures charge and charge demand of thick stock or headbox samples. The technique is polyelectrolyte titration with a cationic polymer solution of known normality and charge density. The titration is carried to the zero streaming current isoelectric endpoint. The two outputs are: (1) Streaming Current starting value before titration, and (2) milliequivalents per liter of charge demand. The standard titrating solution for cationic demand is PolyDADMAC

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(poly-diallyl-dimethyl-ammonium-chloride) and that for anionic demand is PVSK (potassium polyvinylsulfate). The instrument is used to quantify the effect of various additives on system charge, providing a tool for determining optimum additive flow rates.

The ECT system includes a sensor cell, processor, controller, titrating pumps and reservoirs, and a filtering system. The sensor for endpoint determination is the reciprocating piston AC streaming current device similar to that shown in Figure 37. As a stock sample is screened and dispensed into the sensor, particles in the suspension become attached to the teflon piston and cylinder wall of the probe. The consequent ion motion produces the "streaming current" signal measured by the electrodes. The expression which is used for streaming current and electrophoretic mobility is:

 $I = -(16 \pi \mu m s R^2 / c^2) (EM),$

| where | Ι | = streaming current |
|-------|-------------------------------|---|
| | μ | = viscosity of the fluid |
| | m | = motor speed |
| | S | = piston stroke length |
| | R | = radius of piston |
| | с | = clearance between piston and cylinder |
| | EM = electrophoretic mobility | |

The charge demand is determined by adding polyelectrolyte of the opposite charge until a value of zero streaming current is reached.

Thus Charge Demand (meq/l of sample) = (ml of titrant) * (meq/ml of titrant) / (l of sample)

It is asserted that because the electric current is due to the double-layer characteristics of the particles, the charge titrator output is comparable to zeta potential or electrophoretic mobility. The values are, however, numerically equal only at the isoelectric point because of variations in particle charge distributions as well as influences of ionic strength [304]. A portable charge analyzer, the ECA Model 2000, is claimed to have a sensitivity of <1 ppm with an accuracy of 0.01% full scale for a sample volume of 10–200 ml [305].

b Mütek

The on-line Particle Charge Titrator PCT 15[™] has sprung from Mütek's laboratory Particle Charge Detector. It is a reciprocating piston streaming current device similar to that shown in Figure 37. In operation, a sample

slightly greater than 10 ml with a maximum consistency of 1% is metered to the measuring cell and titrated to the isoelectric point. The cationic solution is PolyDADMAC and the anionic one is a sodium polyethylene sulphonate (PES-Na). For consistencies greater than 1%, the stock is filtered with a Thick Stock Sampler (TSS) to remove fibers. Following titration, the cell is emptied, and cleaned with ultrasound and all wetted parts are rinsed with a detergent solution to ensure repeatable results [306,307].

Cited specifications reveal measurements of streaming potential in mV and titrant demand in ml with a 4 to 20 ma output signal and an RS-485 serial interface. An accuracy of up to 0.1% is claimed [308].

One arrangement cited for charge control by Mütek is illustrated in Figure 38 below. Anionic trash control chemical (fixing agent) is metered by a signal from the PCT, added to the low consistency headbox feed stock upstream of the dosage point for retention aid. The method is claimed to maintain an optimum charge level, ensuring maximum performance of the retention aids, metered by a signal from the retention monitor that measures stream consistencies [307].

In order to better combat anionic trash at its source, fixing agents are frequently added to the thick stock. As an improvement on the scheme in Figure 38, in addition to the thin stock sample, a thick stock sample from the machine chest is suitably filtered and sent to another PCT. The PCT signals are processed and fixing agents are metered to both the thick and thin stock flows [309].



Figure 38 A sample Mütek charge/retention control scheme. Redrawn from [307].

c Neles Automation

The on-line kajaaniCATi analyzer measures the cationic demand for consistencies less than 1% with a device similar to that of Figure 37. The measurement is based on titration technology, and the streaming current is used to detect the titration end-point. An optional Chemistry Module is available which measures the temperature, conductivity and pH of the sample. Standard titrating chemicals of PolyDADMAC and PVSK are usually used. Automatic cleaning of the cell is done by pressurized air, water, cleaning chemical and ultrasonic energy to ensure reliable operation. Cited specifications require a sample which has a pH from 3 to 9, a conductivity from 10 to 500 mS/m, a temperature range of 20–60 C with a flow rate >1 l/min. Each measurement cycle for cationic demand in μ eq/l, including cleaning, requires 8 minutes [310].

The Neles Automation philosophy of wet end management is to build an integrated system, considering all key aspects that contribute to wet end stability. Management is based on continuous measurements and the automatic controls pertinent to them. Stability of the wet end is important because of its direct connection to paper machine runnability and MD and CD variations in paper quality.

Consistencies in the short circulation loop are used to monitor first pass retention, stabilizing white water consistency by regulating retention chemical flow. Thick stock consistency and ash content is used in a feedforward manner to prevent disturbances from entering the short circulation loop. Ash control, because of the poor retention, is important for good runnability and printability. Pulp pH has an appreciable effect on papermaking chemistry, affecting chemical efficiency and deposition of soluble components. Charge is one of the basic forces that determines how the chemistry of colloids plays out in the interactions among fibers, fines, fillers, anionic trash, and dissolved and colloidal material in the fluid medium. Conductivity primarily reflects dissolved inorganic material in the process, and is closely related to charge. As conductivity increases, the electrical double layer of the particles becomes thinner, the stability of the colloidal system is reduced, and agglomeration increases.

A skeleton, idealized scheme for overall wet end management is presented below as Figure 39. It is assumed here that pH, temperature and conductivity are under good control before the short circulation loop. The three main subprocesses of consistency, ash and chemistry are based on on-line measurements and individual feedback control, with signals sent to other loops as appropriate for feedforward or interactive information exchange [311].

Referring to Figure 39, any controller-lettered device (such as consistency, KC) is assumed to encompass the appropriate sensor, transmitter and con-



Figure 39 A Neles Automation wet end management scheme. Redrawn from [275]. Courtesy of Neles Automation.

troller functions. First, in the usual fashion, overall basis weight control is achieved by measuring the weight at the reel and adjusting the stock valve SV with the weight controller WC. Thick stock consistency from the blend chest is maintained with controller KC1 which adjusts dilution water valve WV. A signal is sent to the basis weight controller WC as feedforward information.

White water total solids consistency controller KC4 adjusts retention aid valve RV, and in this way stabilizes the retention calculated from headbox and white water total solids consistency controllers KC3 and KC4, respectively. (The consistency sensor was previously described in Figure 30 or 31.)

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Headbox ash consistency is also measured with KC3, and can be used with, or instead of, the reel paper ash controller AC to maintain ash content at the headbox by adjusting filler valve FV2. During normal operation, the paper ash controller AC regulates filler delivery, but during a break, headbox ash control is maintained by KC3. Thick stock filler is controlled by ash consistency controller KC2, regulating filler valve FV1. As feedforward information, a signal is sent to paper ash controller AC during normal operation, and to the headbox ash controller KC3 during a sheet break.

Charge controller EC measures the cationic demand of the white water and regulates polymer valve PV, shown in the short circulation loop as the final control point. This coagulant polymer, which is the anionic trash neutralizing agent, is, in typical cases, added before the short circulation loop to several places with several different controllers, based on cationic demand measurement and the source of the disturbance.

d RAISIO CHEMICALS

Raisio Chemicals provides the WIC 100 wet-end system as a package for supplying real time process control information. The system consists of sampling field equipment, a central analyzing unit, and a chemometric data management/control unit. Measurements typically include cationic demand, dissolved organic carbon, conductivity, pH, temperature, alkalinity, turbidity, silica, calcium, aluminum, and manganese. Analysis takes from three to twelve minutes, while sensors measure variables continuously [312].

e Nalco

In October 2000, Gerli et al. reported on the use of a flocculation sensor to monitor paper machine retention. Several retention schemes using microparticles were evaluated in an alkaline fine paper furnish by using a technique called Non-imaging Reflectance Scanning Laser Microscopy (SLM) or Focused Beam Reflectance Measurement (FBRM). The goals of the studies were to address whether the SLM/FBRM instrument could be used as a predictive tool for retention, and whether it could function for on-line evaluation, optimization, and control of wet-end chemicals.

An on-line probe-type instrument was installed on two pilot paper machines in the supply piping to the headbox, after the addition points of flocculant and microparticles. Operating conditions were between 900 and 1100 m/min, basis weights in the range of 60 to 75 g/m², and ash contents between 18 and 30%. The authors state that headbox flocculation performance results during the several changes in retention program chemistry and dosage levels agreed well with laboratory analyses for constant furnish type

and operating conditions. For production machines, in order to discriminate changes in the flocculation state of the furnish due to retention additives from changes due to other wet end fluctuations, the use of two SLM probes, one before and one after the retention chemical addition point, may be required for the optimization of the additive dose [313].

5 Summary and needs

Particle surface charge and dissolved polymer charge affect many papermaking phenomena, and many mills attempt to measure zeta potential in order to control their process. Commercially available instruments, however, all suffer from one or more drawbacks, such as relying on batch-collected samples rather than a continuous measurement, being restricted to the measurement of the fines fraction, working only at low consistencies, and/or being qualitative in nature. Due to the difficulty of the measurement, most mills rely only on periodic (usually one measurement per shift) laboratory analyses, and use the results for gross wet end chemistry adjustments.

In view of the needs defined by one group (American Forest & Paper Association – AF&PA) and their Agenda 2020, research is needed to develop a new device having characteristics as follows:

- Works over the entire papermaking consistency range;
- Employs a flow-through configuration;
- Employs a simple design for the sensor cell. This permits lower cost, increased reliability, lower maintenance, and implementation of multiple cell configurations;
- Handles a wide range of furnish compositions and particle sizes;
- Is able to be calibrated and standardized.

One newer method under investigation for the measurement of zeta potential is Electrokinetic Sonic Amplitude (ESA). This is a joint academic and industry endeavor to develop a new device for charge measurement over the consistency range of 0.5 to 5%. The technology was stimulated by the technique of acoustic spectroscopy, which is used to characterize particle size distributions 10 μ m and smaller [314]. The basis for the ESA measurement is the converse of an effect discovered by Debye in 1933. Debye found that an AC potential was produced when suspensions of colloidal particles were subjected to ultrasonic waves. These waves perturb the ionic environment around the particles in an oscillatory fashion, giving rise to an alternating voltage potential that is a function of the zeta potential of the particles. By contrast, the ESA device introduces a potential into a cell containing colloidal particles, then "listens" for ultrasound. One assumption made for the device is that the zeta potential of the fibers is equal to that of the filler particles. Another assumption is that the fibers are transparent to the ESA measurement process while the filler particles predominate as the signal source. Preliminary findings indicate that the instrument is well suited for measurement in recycled paperboard mills, and at all locations in fine paper mills where CaCO₃ is used as a filler. For coated fine paper mills using CaCO₃, application might be limited to the thick stock area. For mills that use TiO₂, the required levels are too high for the instrument to be of much use [315].

VI EPILOGUE

My thanks to those readers who have gotten this far. You have suffered through almost 40,000 words - you are to be congratulated. You may have noticed that in at least one way, this paper has been written in the reverse direction from which the papermaking process flows. The first sensors to be discussed were those at the dry end of the paper machine, whereas the last to be discussed were at the wet end. Perhaps Chapter 5 should have been first?

The process of papermaking is changing not only in substance, but character too. While the basic process remains familiar, substantive changes occur in terms of the equipment and processes that are used for forming the sheet, extracting the water and developing certain properties. Character changes are evident in the control of those processes and equipment, the attention paid to diagnostic detail and the elimination of disturbances and irregularities, particularly in the wet end, that plague product uniformity and efficient operation.

Sensor development continues. And in the way of late-breaking news, an on-line X-ray method for paper formation has been recently reported. A large X-ray source is used in conjunction with a two dimensional solid state detector array [316]. But I shall stop here.

The outlook is good. The industry is taking advantage of technological advances to exchange information about the interactions that occur with our physical, chemical and business processes. Real time control of property development, from the standpoint of feedforward information, along with the replacement of some art with science appears on the near horizon. It should be an exciting time.

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Transcription of Discussion

ON-LINE PAPER MAKING SENSORS: AN HISTORICAL PERSPECTIVE

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Mistakes noted in the second volume of the preprints:

Pages 815 and 816:

CyberMetrics FS2D should be: *Techpap FS2D*

Page 837:

CyberMetrics Edge Crack Detector should be: Techpap Edge Crack Detector

Reference 111

"FS2D Formation Sensor," Cyber Metrics, Alpharetta, GA, 2000 should be Eymin Petot Tourtollet, G., "A new two dimensional formation sensor: 2D F sensor", PIRA Conference "Scientific & Technological Advances in the Measurement & Control", Proceedings, Edinburgh Scotland, 9–10 November 1998

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Discussion

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Bo Norman Paper Technology KTH

You have omitted one area I mean fibre size distribution, length and width and fibre shape, was that by design because these parameters are mentioned more and more in Europe but perhaps less in North America.

Mike Waller

I agree.