Paper Drying - Experimental Studies on the Influence of Dryer Fabric

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Amir Farzad Forughi

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The following individuals certify that they have read, and recommend to the Faculty of Graduate and Postdoctoral Studies for acceptance, the dissertation entitled:

Paper Drying - Experimental Studies on the Influence of Dryer Fabric

| submitted by | Amir Farzad Forughi | in partial fulfillment of the requirements for |
|---------------|------------------------|--|
| the degree of | Doctor of Philosophy | |
| in | Mechanical Engineering | |

Examining Committee:

Sheldon Green, Mechanical Engineering Co-supervisor

Boris Stoeber, Mechanical Engineering, Electrical and Computer Engineering

Co-supervisor

Patrick Kirchen, Mechanical Engineering Supervisory Committee Member

C. Jim Lim, Chemical and Biological Engineering

University Examiner

Dana Grecov, Mechanical Engineering University Examiner

Additional Supervisory Committee Member:

James Olson, Mechanical Engineering

Supervisory Committee Member

Abstract

This research is an experimental investigation on paper drying that primarily focuses on the effects of the dryer fabric on the drying process of paper. A novel method for moisture content measurement is presented. The working principle of this method is the strong correlation between the optical transparency of paper and its moisture content due to the refractive index matching role of water in wet paper. Spectrographic and microscopic measurement techniques were employed to characterize the relation of moisture content and relative transparency of paper. As optical access to the paper is restricted by the dryer fabric, the optical transparency of paper should be measured only with one-sided optical access. To achieve this goal, a novel technique of transmittance measurement is developed that is able to determine the transparency of thin film objects (i.e. paper) with only one-sided optical access. Employing a fluorescence imaging method, this optical configuration eliminates the spurious effect of reflection of the incident light by filtering the excitation wavelength before reaching the optical detector.

To study the paper drying process in a multi-cylinder dryer, an experimental setup is designed to simulate realistic conditions of a typical paper dryer while providing optical access for the measurement system. Ten commercially available fabric types manufactured by weaving synthetic filaments are used in the investigations. It is shown that the fabric structure affects the drying progression and the drying time significantly. The contact area and three-dimensional arrangement of the filaments have the greatest impact on the drying process.

To study through air drying (TAD), another experimental apparatus is designed to perform drying under controlled conditions of air temperature and mass-flowrate. Four commercially available TAD fabrics with different structural designs and characteristics are used in the investigations. It is shown that the geometry of the contact spots of the fabrics has a significant impact on the drying time at high drying intensities. Comparing the spatial maps of moisture content with the paper grammage distribution reveals that there is a correlation between the local grammage and the local moisture in a paper sheet during the drying process.

Lay Summary

The drying stage of a papermachine is the greatest energy consumer of the papermaking process. To improve the efficiency of papermaking and reduce the production cost, gaining a better understanding of the effect of different parameters on the drying process is crucial. In the drying stage, dryer fabrics provide mechanical support to paper to increase the runnability and efficiency of the drying process and to prevent non-uniformity and wrinkling. In this research, the effect of the dryer fabric characteristics on paper drying is investigated experimentally. Novel optical measurement techniques are developed and utilized to quantify the moisture content accurately. It is shown that the dryer fabric structure has a remarkable impact on the drying that has not been observed before. The results of this research will lead to the design and development of more efficient fabrics that can reduce the energy cost significantly.

Preface

This PhD thesis entitled "Paper Drying - Experimental Studies" is original work carried out by the author, Amir Farzad Forughi, under the supervision of Professor Sheldon Green and Professor Boris Stoeber. This study was supported by AstenJohnson Inc. and the Natural Sciences and Engineering Research Council of Canada (NSERC). The following contributions have been published or are under consideration for publication:

- A version of chapter 2 has been published as Forughi, A.F.; Green, S. I.; Stoeber, B., Optical transparency of paper as a function of moisture content with applications to moisture measurement, Review of Scientific Instruments, 87(2), 023706, 2016.
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The author of this thesis was the principal contributor to this publication. Prof. Green and Prof. Stoeber supervised the research and assisted with writing the paper.

 The measurement technique presented in chapter 2 and 3 has been publicly disclosed as Forughi, A.F.; Green, S.I.; Stoeber, B., Apparatus for Measurement of Optical Transmission Using Fluorescence Radiation, PCT Patent, WO/2016/134469, 2016. A version of chapter 4 has been presented at the PACWEST conference as Forughi, A.F.; Green, S.I.; Stoeber, B., Moisture Content Measurement in Paper Drying Using a Novel Technique, PACWEST Conference, Whistler, Canada, 2017.

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The author of this thesis was the principal contributor to this publication. Prof. Green and Prof. Stoeber supervised the research and assisted with writing the paper.

• A version of chapter 5 is currently under review with a peer reviewed journal. The author of this thesis was the principal contributor to this publication. Prof. Green and Prof. Stoeber supervised the research and assisted with writing the paper. Albert Kong contributed to this stage of the research under the UBC co-op program. He helped with the construction of the experimental setup and with the experiments.

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List of Symbols

| c_p | Thermal capacitance |
|-----------------------|---|
| D | Diffusion Coefficient |
| g | Body force vector |
| h | Measurement depth |
| Ι | Light intensity |
| I^* | Light intensity of the source |
| I ₀ | Light intensity at reference conditions |
| I _e | Excitation light intensity |
| I_f | Fluorescent light intensity |
| I _i | Incident light intensity |
| k | Relative permeability |
| Κ | Permeability |
| т | Mass sink or source |
| МС | Moisture content |
| n | Refractive index |
| ń | Number of rewetted spots |
| p | Pressure |
| R | Correlation coefficient |
| S | Phase saturation |
| t | Time |
| Т | Transmittance (Transparency) |
| T_e | Transmittance at excitation wavelength |
| T_{e-f} | Transmittance at geometric mean of excitation and fluorescent wavelengths |
| T_f | Transmittance at fluorescent wavelength |
| u | Velocity vector |
| <i>x</i> ₀ | Measurement spatial resolution |
| α | One-half of angular aperture |
| δ | Dirac function |
| Δh_a | Heat of sorption |
| Е | Porosity |
| ζ | Water content |
| $	heta_i$ | Angle of incident light |
| θ_t | Angle of transmitted light |
| λ | Wavelength |

| λ_e | Excitation wavelength |
|-------------|--|
| λ_f | Fluorescent wavelength |
| λ_s | Effective conductivity |
| μ | Dynamic viscosity |
| μ_a | Light absorption coefficient |
| μ_s | Light scattering coefficient |
| μ_t | Light extinction coefficient |
| ν | Kinematic viscosity |
| ρ | Density |
| τ | Amplitude ratio of electric field of the transmitted to the incident light |
| Υ | Transmission ratio |
| Ω | Emission angle |
| | |

List of Abbreviations

| CD | Cross Direction |
|-------|--|
| CMC | Critical Moisture Content |
| CTMP | Chemi-ThermoMechanical Pulp |
| DAQ | Data Acquisition |
| HWA | Hot Wire Anemometer |
| IMITO | Index Matched Indium Tin Oxide [™] |
| IR | Infrared |
| ITO | Indium Tin Oxide |
| LED | Light Emitting Diode |
| MC | Moisture Content |
| MD | Machine Direction |
| MFC | Mass Flow Controller |
| NA | Numerical Aperture |
| NBSK | Northern Bleached Softwood Kraft |
| ND | Neutral Density |
| NIR | Near-Infrared |
| OCT | Optical Coherence Tomography |
| PID | Proportional Integral Derivative |
| RH | Relative Humidity |
| RI | Refractive Index |
| sCMOS | Scientific Complementary Metal-Oxide-Semiconductor |
| T/C | Thermocouple |
| TAD | Through Air Drying |
| TIR | Total Internal Reflection |
| UBSK | Unbleached Northern Bleached Softwood Kraft |
| UFT | Unsaturated Flow Theory |
| UV | Ultraviolet |
| μPAD | Microfluidic Paper-Based Analytical Device |
| | |

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Dedication

To my parents.

Chapter 1: Introduction

1.1 Motivation

1.1.1 Multi-cylinder Drying

Paper products are remarkable inventions. Paper is a very reliable medium for information storage and dissemination, an environmentally friendly packaging material, the essential material for hygiene products, and the cheapest substrate for lab-on-a-chip devices. The pulp and paper industry is one of the major manufacturing industries in the world and is particularly prominent in Canada. To increase market competitiveness and achieve a reliable profit margin, manufacturers need to reduce production costs, which can be accomplished in part by optimizing the energy consumption of the paper machines. This pressure has led to the expenditure of considerable effort by researchers to optimize the energy use in paper machines.

Most paper machines have three major operational stages – the forming section, in which a wet paper mat is made from a pulp slurry; the press section, in which the pulp mat is mechanically dewatered and consolidated; and the drying section, in which the paper moisture content is reduced from about 130% to about 8% by weight (Figure 1.1). Here the moisture content (MC) is defined as the mass of water per mass of dry paper. 50% to 80% of the total energy in paper production from pulp is consumed by the drying section [1–3]. The high latent heat of vaporization of water is responsible for the high energy cost of drying. Multi-cylinder dryers [1, 4, 5] are the dominant configuration used in the paper industry. In multi-cylinder dryers, the paper web is brought into contact with steam-heated cylinders. Typically, the surface temperature of the cylinders may vary from 80°C to 140°C depending on the position of the cylinder and the papermachine type [1, 5]. A woven dryer fabric presses the paper onto the surface of the cylinders to reduce the heat transfer contact resistance. Typically, the paper web travels through the machine at approximately 15 m/s,

however modern papermachines may exceed the production speed of 30 m/s [1]. All dryer cylinders are enclosed in a well ventilated hood to remove the humid air and boost evaporation.



Figure 1.1 The schematic of a typical paper machine. (The drawing is not to scale.)

The drying process in multi-cylinder dryers is well studied. Numerical simulations and experimental investigations have been conducted to quantify the effect of different factors (such as operating parameters, ventilation, paper type, etc.) on the efficiency of the drying [6–11]. These investigations have led to significant efficiency improvements in the drying process [3, 5, 6, 8, 11–18]. The process of heat and mass transfer in typical multi-cylinder dryers consists of four major phases [19]. As sketched in Figure 1.2, the paper sheet starts to be in contact with the cylinder surface in phase 1 while the other surface of the web is exposed to the air. In phase 2, the dryer fabric covers the surface of the paper and presses the paper onto the cylinder surface. The sheet surface becomes exposed to the air again as the fabric detaches and is not in contact with the paper in phase 3. In phase 4, which is called the free or open-draw phase, the sheet is no longer in contact with the cylinder and both sides are exposed to the surrounding air. The mechanisms of heat and

mass transfer are different in each phase of drying. Studies have shown that in phases 1 and 3 the rate of evaporation and heat transfer are relatively low [10]. The heat transfer rate is maximum in phase 2 as the fabric's pressure improves the heat transfer efficiency to the paper. Most evaporation occurs in phase 4 as the paper surfaces are not blocked by the fabric or the cylinder surface [2, 10, 20].



Figure 1.2 Drying phases in typical multi-cylinder dryers. The drawing is not to scale.

In specific applications, dewatering must continue to a lower moisture level than the 8% that would be needed in regular drying. Such excessive drying might be necessary before the size press or in case the MC profile is spatially uneven [1]. In the size press stage, a specific material such as starch is applied to the surface of the paper to enhance the resistance to fluid penetration and to improve the surface strength. The evaporation rate and drying capacity of a contact dryer decreases exponentially at low moisture contents, and therefore a longer dryer section with more cylinders is needed to reach the goal MC for excessive drying. This results in a much higher energy cost for removing an equal mass of water [1]. Inefficient heat transfer at low moisture contents is reported to be responsible for the drying capacity reduction in excessive drying [1, 21]. It has been shown

that increasing the fabric tension can improve the excessive drying rate significantly [1]. As the distribution of the mechanical pressure on the paper is a function of fabric properties, the fabric structure impacts the local drying rate. During drying, the spatial non-uniformity of moisture content increases the drying cost and reduces the drying capacity [1, 22]. It also reduces the product quality significantly causing cockling and curl in the paper web [22].

Heat and mass transfer in phases 1, 3 and 4 and the thermodynamics of the whole dryer have been studied previously. However, due to the lack of physical access to the paper and absence of an accurate measurement technique, phase 2 heat and mass transfer has been the least understood part of the whole drying process [1].

As discussed in section 1.2, traditional measurement methods are unable to quantify the moisture content of paper with high resolution and accuracy when physical access to the paper is restricted. More importantly, none of these techniques is able to measure the moisture content non-disruptively while paper is sandwiched between the fabric and the heater surface. Additionally, the majority of numerical and analytical studies have utilized simplified heat and mass transfer models that consider the cylinder-paper-fabric as a one-dimensional system (described in sections 1.3.1 and 1.3.2). In these models the dryer fabric is considered only through its impact on the overall conductivity and permeability [1, 5, 23].

Evidently, the dryer fabric plays an important role in the second phase of drying as it affects the heat and mass transfer to and from the web [2, 24] (Figure 1.2). The main role of the dryer fabric is to make drying fast and uniform, which improves efficiency and product quality. A secondary role of the dryer fabric is to improve the reliability of paper production by supporting the web during drying. By studying the whole dryer thermodynamics, previous investigations have shown that, provided the fabric is sufficiently permeable, the fabric permeability does not significantly

4

impact the drying rate [5, 25]. It has also been established that fabric tension is positively correlated with the drying rate [5, 26, 27]. However, the effect of fabric structure on drying has not been previously reported despite the fact that the geometric structure of fabric might affect the drying through its impact on the heat transfer contact resistance.

1.1.2 Through Air Drying (TAD)

Through air drying (TAD) provides the highest drying rate compared to other traditional paper drying techniques such as contact drying and impingement drying [1]. In TAD, hot air or combustion products pass through the paper (or textile) in order to evaporate the water (Figure 1.3). Due to the large effective surface area, TAD can reach drying rates as high as $400 kgH_2O/m^2h$, which is an order of magnitude higher than the typical drying rate in contact drying [28]. TAD is particularly effective for highly permeable papers such as paper towel and tissue. TAD also improves the softness, absorbency and hand feel of paper by reducing the structural consolidation of the final product [28]. Although the high energy consumption of TAD makes it costly, it reduces raw material expenses by increasing the bulk and reducing the required grammage to achieve similar product quality as other techniques.



Figure 1.3 The schematic of a through air dryer (TAD). (The drawing is not to scale.)

Early research on TAD focused on the fundamentals of the drying process as well as the growing significance of this drying method [29–31]. TAD drying has been studied by various numerical and experimental methods. Some numerical and semi-analytical models were introduced to simulate the TAD process and investigate the effects of paper structure, grammage, pore size distribution, drying parameters, and the psychrometric properties of the air [32, 33]. TAD under industrial conditions has also been modeled to study the effect of operating conditions on energy efficiency [34, 35]. Using computational fluid dynamics (CFD) simulation, the effect of non-uniformity on fluid flow and heat and mass transfer in TAD was investigated [36]. However, numerical models often use simplifications and assumptions with weak or no empirical proof [32].

Generally, the paper drying process consists of three major stages: increasing drying rate, constant drying rate and falling drying rate [1, 30, 37]. In the first stage of drying, also called the

warmup stage, the time derivative of the drying rate is nearly constant [30]. Experimental studies of low grammage papers under different flow conditions have shown that, unlike in contact drying, the constant drying rate stage does not exist in TAD as long as the intensity of drying is not very low [30, 38]. Thus, in TAD, after the warmup stage, the drying rate starts decreasing at a transition point called the critical moisture content (CMC). It has been shown that, in TAD, the CMC is primarily a function of initial moisture content and drying conditions such as air temperature and flowrate [30, 31], unlike in contact drying where paper properties mostly determine the CMC value [1]. It has been shown empirically that mass transfer in TAD can be described using the relation of the Sherwood number Sh and the Reynolds number Re as Sh \propto Reⁿ where the exponent n is a function of paper properties and drying conditions [30, 31, 39].

Investigations of hybrid systems of impingement-TAD [40–42] and contact-TAD [43, 44] have revealed that air properties and paper structure have a significant impact on drying. The main advantage of the hybrid contact-TAD systems is that the drying process can be optimized in a way that minimizes drying time and the undesirable effects of drying non-uniformity. Experimental investigations of TAD under realistic conditions on a papermachine have emphasized the significance of air temperature, flow rate, the paper formation process and pulp properties [28, 37, 45–48]. Most experimental studies utilized a nearly identical experimental approach in which the water content of air before and after the paper sheet is used to quantify the evaporated moisture from the paper web. In some studies, the moisture content and the temperature of the web is measured using infrared (IR) measurement methods simultaneously [28].

The high drying intensity of TAD is beneficial for paper production but it makes the study of the drying process challenging. The entire drying process at high temperature and flowrate (high drying intensity) may occur within fractions of a second. This means that all important variables, in particular the moisture content MC, should be recorded with high temporal resolution. This requirement may reduce the accuracy of the measurement. Additionally, traditional moisture content measurement techniques are not capable of resolving moisture distribution with high spatiotemporal resolution while optical or physical access to the paper is restricted [31, 37, 38, 42, 48]. IR measurement techniques are capable of resolving the spatial distribution of moisture, although optical access to both sides of the paper is necessary for this technique. In IR techniques, the moisture content gradient in the depth of paper may cause significant measurement errors [49, 50]. Some research has been carried out to resolve the depth gradient problem using IR hyperspectral imaging but direct access to both sides of the paper sample is essential [49]. It has also been shown that the temperature effect on IR moisture measurement is significant [50] and therefore temperature maps during the measurement are necessary to recalibrate the results. Although drying non-uniformity has been investigated using a combination of multiple IR reflection sensors at different positions above the paper sheet [22], an effective measurement technique with the ability of quantifying moisture content with high spatiotemporal resolution and accuracy is absent from the literature. Additionally, the effect of the through air dryer fabric on the drying efficiency in TAD has not yet been investigated.

1.1.3 Research Objectives

To address the identified research gaps, this thesis focuses on the following objectives:

1. Development of a measurement method that is able to quantify the moisture content of paper with high accuracy and resolution. The spatiotemporal resolution must be high enough to resolve the moisture content at a scale smaller than the fabric weave pattern $(\sim 2 mm)$ and the drying process time scale (a few seconds for contact drying). This

technique must be non-disruptive and functional while the paper is sandwiched between the dryer fabric and the heater surface.

- 2. Investigation of the effect of different parameters such as psychrometric properties of the air, the temperature of the heater, and the dryer fabric properties on drying. Using the developed measurement method, the second phase of contact drying under realistic conditions of a typical multi-cylinder dryer and with commercially available dryer fabrics should be investigated. Guidelines for selection of contact dryer fabrics for different applications should be established.
- 3. Investigation of the effect of the dryer fabric, air flowrate and temperature on the drying of paper in through air drying. The effect of fabric characteristics under different drying conditions should be investigated.

1.2 Measurement of Paper Moisture Content

1.2.1 Traditional Moisture Content Measurement Techniques

Currently, the paper-making industry uses traditional methods for measuring moisture content in paper, such as the gravimetric method, near infrared (NIR) spectroscopy and nuclear attenuation gauges. The gravimetric method is the easiest way of measuring moisture content, but direct access to the sample is required. The difficulties of sampling, due to the lack of access in most cases, make it inapplicable for transient measurements. NIR spectroscopy provides fairly good measurement resolution, though it is expensive and because of sample and water absorption overlap in the infrared spectrum, calibration is challenging and inaccurate in some cases [51]. Commercial NIR tools are designed for a cumulative measurement over a relatively large sample area of several square millimeters. This resolution is adequate for paper machine control purposes but is not sufficient for resolving moisture locally at the scale of the paper sheet thickness; such

local measurements are required to study the drying or wetting process in paper, in particular when the paper is partially constrained by impermeable objects. Nuclear attenuation gauges (e.g. beta and gamma gauges) are rarely used for moisture measurements because they are expensive and unsafe [52, 53].

A number of new techniques for moisture measurement are currently under development. Many microwave techniques have been recently developed for moisture content measurement [54–57]; these techniques provide a good resolution of the moisture content although their spatial resolution of 20 mm is not sufficient to study the local transport of moisture in paper that occurs during drying. Additionally, these microwave techniques only have a very small working range of 9% to 30% moisture content (percentage of mass of water / dry mass of paper) [54, 57]. Since there is a correlation between electrical characteristics of paper and its moisture content, some moisture measurement techniques have been developed based on impedance [58], dielectric properties [59] and electromagnetic field perturbation [60]. These methods have numerous limitations such as a small working range in terms of humidity and a very low spatial resolution on the order of centimeters; however, some of these methods can provide a local cumulative measurement with good accuracy (0.3%) and time resolution (100 ms) [61]. In summary, no previously documented moisture measurement method is suitable to be used while the access to the paper is restricted, as it is in the second phase of drying.

1.2.2 Optical Transparency as a Function of Moisture Content

In this research, an alternative method for moisture measurement in paper is developed that takes advantage of the correlation of optical transparency of paper with moisture content. This method has the advantage that optical transmittance can be measured effortlessly with high spatiotemporal resolution. Paper, as a highly anisotropic porous system of cellulose fibers, fillers, fines and air, strongly scatters light due to the high refractive index (RI) difference between its solid components and air (Table 2.1). This scattering attenuates the transmitted light intensity and hence reduces the optical transparency of the medium [62]. By increasing the moisture content of paper, water fills the pores of paper which were previously occupied by air. Owing to the fact that water has an RI closer to the RI of the solid components of paper, water acts as an RI matching agent and increases the optical transparency of paper (Figure 1.4).



Figure 1.4 In dry paper, a larger RI difference between the solid mesh and the air-filled pores results in less optical transmittance.

When a light ray in a material with refractive index n_1 strikes the interface with a material with refractive index n_2 , it is reflected or transmitted. If the incoming light has angle θ_i relative to the normal to the interface, then the transmitted light has an angle θ_t normal to the interface, as governed by Snell's Law:

$$n_2 \sin \theta_t = n_1 \sin \theta_i. \tag{1.1}$$

The amount of light that is transmitted is a function of the polarization of the incoming light. The incoming light may be polarized in the plane of the refraction (parallel polarization, *p*, denoted by the subscript \parallel) or in the perpendicular polarization (*s*, denoted by the subscript \perp). The ratio of the transmitted to the incident wave electric field amplitude is given by τ , which has two components, τ_{\parallel} and τ_{\perp} . The component of τ for *p*-polarization is given by

$$\tau_{\parallel} = \frac{2n_1 \cos \theta_i}{n_1 \cos \theta_t + n_2 \cos \theta_i} \tag{1.2}$$

and for *s*-polarization is given by:

$$\tau_{\perp} = \frac{2n_1 \cos \theta_i}{n_1 \cos \theta_i + n_2 \cos \theta_t} \tag{1.3}$$

The Fresnel equation [63] then gives the ratio of transmitted light to incident light

$$\Upsilon = \frac{n_2 \cos \theta_t}{n_1 \cos \theta_i} |\tau|^2. \tag{1.4}$$

Therefore a larger difference in refractive indices n_1 and n_2 reduces the transmission ratio Υ . Total internal reflection (TIR) is another phenomenon responsible for light scattering in paper. TIR occurs when a light ray strikes an interface at angles larger than the critical angle of refraction that yields $\theta_t = 90^\circ$. This critical angle can be calculated using Equation (1.1) as $\theta_{critical} = \arcsin(n_2/n_1)$. Both Fresnel refraction and TIR imply that a smaller difference in the RI of materials at an interface, as for example occurs when water replaces air in a paper matrix, increases the transmitted light through the medium.

To calculate the transmittance of a discrete two phase system, a theory was developed by Conaghan and Rosen [64] that considers a single scattering event of a light ray by scattering elements. As this theory neglects higher orders of light scattering, it is inaccurate for high volume fractions of scattering particles or a porous matrix [65]. Additionally, it is still necessary to solve Maxwell's equations to calculate the scattering coefficient; some approximation formulas have been proposed for limited cases, such as a small RI difference and scattering particles substantially larger than the wavelength of the light [66]. Due to the random and complex structure of paper, none of these theoretical approaches can produce an accurate prediction of light transmittance through paper; instead, Monte Carlo simulations can be utilized for studying the interaction of light and paper if the structure and elements of paper are known [67].

The effect of RI matching on optical object detection in paper was studied by Saarela et al. [68]. They investigated the effect of the addition of liquids with different RIs on the transparency of paper. They found that the lower the difference between the RIs of the liquid and the paper, the more transparent the paper becomes. This means that the highest degree of transparency can be achieved for a liquid with an RI that is closest to the RI of the paper's dry material. Using different refractive index matching liquids, Fabritius et al. [62] measured the RI of dry paper. Making optically clear paper by RI matching can be beneficial to study the internal structural of paper using optical methods such as Optical Coherence Tomography (OCT) [69-71]. Also, making optically clear paper permits accurate measurement in microfluidic paper-based analytical devices (μ -PAD), which have broad applications in chemical and biological diagnostics [72, 73]. Rodriguez et al. [74] used the dependence of the transparency on moisture in the infrared to measure the moisture content in oil-paper insulation of power transformers. Such measurements rely on the strong absorption of water in the infrared, not on index of refraction effects. Karppinen et al. [75] have studied the process of paper wetting over time by qualitative measurement of paper transmittance. However, moisture content was not quantified in their study.

Conventional transmittance measurement systems work based on quantifying the intensity of light passed through a sample and comparing it to the light source intensity on the other side of the sample. In such a system, optical access to both sides of the sample is necessary for illumination and measurement. The necessity of access to both sides leads to a bigger measurement apparatus and does not allow measurement when the sample is optically blocked on one side (as it is in the

multi-cylinder paper dryer). According to Kubelka-Munk theory, the transparency of thin sheets can be measured from one side if the other side is covered with a surface of known optical reflectance. This technique has been used for the measurement of brightness, opacity and fiber bonding of paper sheets [76]. However, this technique's assumptions and limitations, such as the necessity of repeating the measurement with a number of layers and direct access to the sample, make it inappropriate for moisture content measurement [76, 77]. To measure moisture content when paper is blocked by the fabric on one side, a new optical technique must be developed that is able to quantify the optical transparency when access to the paper is restricted. As described in chapter 3, using a novel fluorescent imaging technique, measuring the optical transparency of paper (or other translucent films) becomes possible.

1.3 Fundamentals of Water Transport in Paper Drying

Transport phenomena in porous media are highly complicated, which makes analytical investigations challenging [78]. This section briefly summarizes the widely used model of water transport in paper as well as the heat and mass transfer in the dryer.

1.3.1 Unsaturated Flow Theory (UFT)

In the dryer section of a paper machine, the paper is not saturated with water; some pores completely or partially contain air. The air-water-paper system forms a multiphase system that includes a liquid-air-solid contact line that cannot be analyzed using simple models such as Darcy's law. To take the capillary pressure p_c into account, an approximate model called the unsaturated flow theory (UFT) was developed [79, 80]. In this model, the capillary pressure is directly proportional to the interfacial tension (surface tension of water and the contact angle of the water-air interface on the fibers) and inversely proportional to the pore size that defines the
radius of curvature of the capillary [78]. The capillary pressure is also a function of the phase saturation, s, which is defined as

$$s = \frac{MC}{MC_{sat}},\tag{1.5}$$

where MC_{sat} is the saturation moisture content. It is reported that although p_c is a monotonic function of phase saturation in imbibition and drainage, the value of p_c , at a particular saturation level, differs depending on whether the paper is imbibing or draining water [78].

In the unsaturated regime, the cross sectional area of each fluid phase is restricted to a smaller area compared to the saturated case. This smaller cross section leads to a smaller effective permeability that may be described by:

$$k_{effective} = k_r K \tag{1.6}$$

where, *K* is the intrinsic permeability at saturation conditions and $0 \le k_r \le 1$ is called the relative permeability [78]. The value of relative permeability for each porous medium and phase should be determined empirically.

In a non-deformable porous medium with porosity ε and fluid density ρ , the mass conservation equation can be defined as:

$$\varepsilon \frac{\partial(\rho s)}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = \overline{m}, \qquad (1.7)$$

where **u** is the fluid phase velocity vector and \overline{m} is the mass sink or source of the fluid phase. Similarly, the momentum equation is:

$$\mathbf{u} = -K \frac{k_r}{\mu} (\nabla p - \rho \mathbf{g}), \qquad (1.8)$$

where \mathbf{g} is the vector of body force (gravity). This is the generalized Darcy equation and is valid if inertia and macroscopic viscous effects are neglected [78]. Assuming that the pressure of the gas phase is constant and atmospheric, the pressure gradient would be:

$$\boldsymbol{\nabla} p = \boldsymbol{\nabla} p_g - \boldsymbol{\nabla} p_c = \boldsymbol{\nabla} (\rho_g \mathbf{g}) - \frac{\partial p_c}{\partial s} \boldsymbol{\nabla} s.$$
(1.9)

Index g refers to the gas phase. By substitute Equations (1.8) and (1.9) into Equation (1.7), the mass conservation equation becomes:

$$\varepsilon \frac{\partial(\rho s)}{\partial t} + \nabla \cdot \left(K \frac{k_r}{\nu} \frac{\partial p_c}{\partial s} \nabla s \right) + \nabla \cdot \left(K \frac{k_r}{\nu} (\rho - \rho_g) \mathbf{g} \right) = \overline{m}, \tag{1.10}$$

Defining diffusivity D(s) as:

$$D(s) \triangleq -K \frac{k_r}{\nu} \frac{\partial p_c}{\partial s},\tag{1.11}$$

reduces Equation (1.10) to:

$$\varepsilon \frac{\partial(\rho s)}{\partial t} - \nabla \cdot (D(s)\nabla s) + \nabla \cdot \left(K \frac{k_r}{\nu} (\rho - \rho_g) \mathbf{g}\right) = \overline{m}.$$
(1.12)

This equation in the steady state form $(\partial(\rho s)/\partial t = 0)$ and in absence of a body force ($\mathbf{g} = 0$) and interphase mass transfer ($\overline{m} = 0$) forms the Richards equation that can be solved easily.

The main challenge of using Equation (1.12) to model the water transport in paper is that the value of the diffusivity D(s) is difficult to quantify. Many empirical studies have been conducted to measure the diffusivity for well-known standard papers (e.g. WhatmanTM papers) [81–87]. However, the reported values have orders of magnitude of inconsistency. The reason for this mismatch is reported to be a combination of different factors such as inconsistency of environmental conditions, inconsistency of paper samples, and the uncertainty of the evaluation method [87]. It should be noted that regular paper types with oriented fibers have a high level of structural anisotropy and the diffusivity must be evaluated separately for all three directions. In

contrast, handsheet paper is laterally isotropic due to the random orientation of the fibers, but the diffusion coefficient is different in the depth of the paper (the "z-direction"). These complications make analytical modeling and numerical simulation of water transport at the filament scale inaccurate and unreliable [1, 87].

1.3.2 Heat and Mass Transfer Analysis

Relatively basic heat and mass transfer models have been employed to understand multi-cylinder drying. As sketched in Figure 1.5, these models simplify different phases of drying to a multilayer system of steam-condensate-cylinder, wet paper, dryer fabric and air. During each phase of drying, the model includes one or more parts of the multilayer. In phase 2, the effect of all parts of the multilayer must be considered [88]. To improve the accuracy, some researchers resolved the radial and tangential heat transfer in the cylinder shell and paper using computational fluid dynamics (CFD) simulations. Experimental investigations have been carried out to quantify the macroscopic effects of steam-condensate-shell, paper and fabric-air layers [1, 23, 89–91]. The findings of those investigations will be discussed in chapter 4.



Figure 1.5 Multilayer model for different phases. The drawing is not to scale.

The governing equation of the heat transfer in the model presented by reference [1] is as follows:

$$\rho c_p \frac{\partial T}{\partial t} = \lambda_s \frac{\partial^2 T}{\partial z^2} + \frac{\partial \lambda_s}{\partial T} \left(\frac{\partial T}{\partial z}\right)^2 - \left(\frac{\dot{m}_v + \dot{m}_w}{A}\right) \left(c_p + \frac{\partial \Delta h_a}{\partial \zeta} \frac{\partial \zeta/\partial z}{\partial T/\partial z}\right) \frac{\partial T}{\partial z}, \quad (1.13)$$

where T is the temperature of the paper at time t and depth z in the thickness of the paper. The terms ρ and c_p are the density and the thermal capacitance, respectively. λ_s is the effective conductivity of wet paper, which is a function of water content $\zeta = MC/100$. The term Δh_a is the heat of sorption, which is significant in the hygroscopic region (low moisture content and high relative humidity) [1]. \dot{m}_v and \dot{m}_w are time derivatives of mass of vapor and water, respectively. The mass conservation equation for the water phase is:

$$\rho \frac{\partial \zeta}{\partial t} = -\frac{\partial}{\partial z} \left(\frac{\dot{m}_v + \dot{m}_w}{A} \right). \tag{1.14}$$

In most simulation applications, Equations (1.13) and (1.14) are solved numerically. The most challenging part is defining the equation constants and the boundary conditions that must be evaluated experimentally [1, 5, 10].

Although bulk thermodynamic models are useful for energy analysis and optimization of the dryer section, they don't provide detailed information about the transport phenomena in every phase or step of the drying process, and certainly not at the scale of dryer fabric filaments, which is one of the focus areas of the research described here [88, 89].

1.4 Outline of the Thesis

This thesis concerns primarily the experimental study of paper drying and the impacts of the dryer fabric, although there are also novel measurements of paper wetting presented. The thesis is structured as follows:

- Chapter 2 presents a novel method for moisture content measurement. The operating principle of this method is the strong correlation between the optical transparency of paper and its moisture content. Spectrographic and microscopic measurement techniques were employed to characterize the relation of moisture content and relative transparency of four types of paper: hardwood chemi-thermomechanical pulp (CTMP) paper, Northern bleached softwood kraft (NBSK) paper, unbleached softwood kraft (UBSK) paper and General Electric[®] Whatman[™] grade 1 chromatography paper. It was found that, for all paper types, the paper transparency increased monotonically with the moisture content (as the ratio of the mass-of-water to the mass-of-dry-paper increased from 0% to 120%). This significant increase in transparency occurred due to the refractive index matching role of water in wet paper. It is further shown that mechanical loading of the paper has little impact on the relative transparency, for loadings that would be typically applied to paper on a paper machine. The results of two transient water absorption experiments are presented that show the utility and accuracy of the technique.
- A novel technique of transparency measurement is presented in chapter 3 that is able to determine the transparency of thin film objects with optical access limited to just one side. This method involves mounting the object on a fluorescent substrate, illuminating the object at an excitation wavelength, and observing the light radiated from the object at the fluorescence wavelength. The observed intensity of the light at the fluorescence wavelength is directly related to the transmittance of the object at the excitation and fluorescence wavelengths. The spurious effect of reflection of the incident light is eliminated by filtering the excitation wavelength before reaching the optical detector. The technique was used to measure the transmittance of neutral density filters, which were also

measured using a conventional transmittance configuration. The difference between the transmittance measured using one-sided optical access and the conventional two-sided configuration was 2.4% or less. To prove the utility of the technique, the transmittance of paper was measured during drying, while the paper sample was sandwiched between a woven dryer fabric and a heater. The relationship between the optical transmittance of paper and its moisture content has been determined in chapter 2, and this relationship was used to infer the moisture content of the paper during drying. The moisture content distribution during the drying process is shown to be spatially correlated with the structure of the dryer fabric.

• Using the optical measurement method developed in chapters 2 and 3, the moisture content of paper can be accurately quantified at high spatial and temporal resolution while it is sandwiched between the heater surface and the dryer fabric, as shown in chapter 4. To study the paper drying process, an experimental setup is designed to simulate realistic conditions of a typical paper dryer while providing optical access for the measurement system. Ten commercially available fabric types manufactured by weaving synthetic filaments are used in the investigations. The three-dimensional structure of the fabrics is characterized using optical coherence tomography (OCT). The fabrics are used in the experiments to investigate the effects of the filament structure, covered area, and contact area of the fabrics on the drying process. It is shown the fabric structure affects the drying progression and the drying time. Fabrics that have a relatively large drying rate at high paper moisture content may have a relatively small drying rate at low levels of moisture content. The contact area and three-dimensional arrangement of the filaments have the greatest impact on the drying process. Adjacent filaments result in larger blocked regions

and reduce the drying rate. The spatial distribution of moisture as a function of time reveals that frequent rewetted spots appear during the drying. These rewetting spots are caused by reabsorption of water condensed on the fabric filaments.

An experimental apparatus is designed to perform through air drying under well-controlled drying conditions such as air temperature and mass-flowrate. The spatial distribution of moisture content in paper during through air drying is quantified as a function of time in chapter 5. The technique is capable of measuring the moisture content distribution with high spatiotemporal resolution while air flows through a paper mat sitting on a permeable dryer fabric. Four commercially available fabrics with different structural design and properties are used in the investigations. The effect of the fabrics' structural properties, which are characterized using OCT, is studied under various drying conditions. It is shown that the geometry of the contact spots of the fabrics has a significant impact on the drying time at high drying intensities. However, at low rates of drying (i.e. low air temperature and flowrate), no correlation between drying time and fabric properties is observed. After a cycle of through air drying, the permeability of paper increases irreversibly. This increased permeability is observed to be a function of the fabric structure. It is shown that the increase in permeability is larger for coarse fabric structures although no monotonic correlation with the fabric permeability can be observed. Comparing the spatial maps of moisture content with the paper grammage distribution reveals that there is a correlation between the local grammage and the spatial pattern of drying in paper a sheet.

Chapter 2: Optical Measurement of Moisture Content

2.1 Introduction

In this chapter, the effect of moisture content on the spectral transparency of four different wellknown types of paper is determined using a spectrographic characterization setup [92]. It is shown that the monotonic correlation of moisture content and optical transparency can be used for moisture content measurement. To prove the utility of the technique, the results are then applied to two different paper wetting experiments using a microscopic imaging setup to generate 2D moisture content maps over time.

2.2 Materials and Methods

2.2.1 Paper Samples

Four different types of paper samples are used for the experiments in this study; I) hardwood chemi-thermomechanical pulp (CTMP) paper, II) Northern bleached softwood kraft (NBSK) paper, III) unbleached softwood kraft (UBSK) paper and IV) General Electric[®] Whatman[™] grade 1 chromatography paper. The CTMP paper was produced by thermal and mechanical refining of hardwood chips with an average fiber length of 1 mm after processing. Bleached and unbleached softwood papers were made from bleached and unbleached northern softwood kraft respectively, which are the industry's benchmark grade pulps in North America with an average fiber length of 2.5 mm. For all CTMP, NBSK and UBSK samples, the orientation of the fibers is random since the samples were made as handsheets in a laboratory and not on a paper machine. These paper samples were prepared based on the standard TAPPI procedure (T205 sp-02). Whatman grade 1 chromatography paper is the world standard chromatography paper. It contains pure cellulose produced from cotton linters with no additives. The grammage and thickness of the paper samples and their non-uniformity across a hand sheet are given in Table 2.2 for fully dry paper. The non-

uniformity of the fiber distribution, the grammage, and the thickness are very important parameters since they can affect the accuracy of the measurements by changing the paper's optical characteristics and therefore represent a potential source of error [93]. The RI values for the experimental materials in Table 2.1 show that the RI difference of the dry paper fibers and its pores decreases significantly from 0.557 to 0.228 if the pores are filled with water instead of air (neglecting the effect of imbibed water).

Table 2.1 Refractive indices of the experiment materials at standard temperature and pressure. [62, 94]

| Material | Refractive index | | |
|----------------------------|-------------------------|--|--|
| Air (Dry) | 1.000 | | |
| Glass | 1.518 | | |
| Water | 1.329 | | |
| Pure Cellulose | 1.469 | | |
| Softwood Kraft Paper (Dry) | 1.557 | | |

Table 2.2 Grammage and thickness of dry paper samples.

| Paper Type | Grammage | Thickness | | |
|------------|--------------------|--------------------------|--|--|
| СТМР | $63 g/m^2 \pm 4\%$ | $94 \ \mu m \ \pm \ 4\%$ | | |
| NBSK | $54 g/m^2 \pm 5\%$ | 97 $\mu m \pm 5\%$ | | |
| UBSK | $60 g/m^2 \pm 5\%$ | $115 \mu m \pm 6\%$ | | |
| Whatman | $87 g/m^2 \pm 2\%$ | $173 \mu m \pm 2\%$ | | |

During the experiments, water was added to the fully dried samples using a micropipette, and a sensitive balance was used to confirm the added mass of water. After adding water, the samples were kept in a narrow $(20 \times 20 \times 0.2 \text{ }mm^3)$ insulated chamber, made of silicone gaskets and microscope glass slides, for 10 minutes (for a $10 \times 10 \text{ }mm^2$ sample) to allow enough time for the moisture to be distributed uniformly in the samples. No change was observed if the samples

equilibrated for more than 10 minutes. The chamber was returned to the balance to confirm the amount of added water. Afterwards, the sealed chamber was positioned carefully into the optical transmission setup.

2.2.2 Experimental Setup

The optical transmittance of paper was characterized using two different setups: 1) spectrographic characterization 2) microscopic imaging. Schematics of both experimental setups are shown in Figure 2.1 and Figure 2.2.



Figure 2.1 The schematics of the spectrographic characterization setup.



Figure 2.2 The schematics of the microscopic imaging setup.

2.2.2.1 Spectrographic Characterization

To capture spectral data the spectrographic characterization setup shown in Figure 2.1 is used. To investigate the fluorescent yield of the samples an Optometrics® tunable monochromator is utilized to control the wavelength (λ) of the excitation light accurately. A tungsten halogen lamp is employed as the main light source of the monochromator and the output light is tunable in the 400-800 nm range (visible spectrum) using a motorized mechanism with a spectral emission band of 6 nm. The transmitted light is collected by a collecting lens system that is connected to a fiber optics system to deliver the light to an AVANTES® AvaSpecTM spectrograph for decomposition and analysis. The spectrograph is able to measure the absolute and relative intensity of light in the range of 380 – 900 nm with a spectral resolution of 1.2 nm. By combining the spectrograph and

the monochromatic light source, the pure relative transmittance and fluorescent emission are measured simultaneously for each illumination wavelength produced by the monochromator. The measuring spot of the spectrographic setup is circular (4 mm diameter) and by capturing five successive data sets with an exposure time of 100 ms and averaging, the uncertainty of the spectrograph for each measurement is smaller than 0.1%. The uncertainty of the final result for a specific position of a sample is smaller than 3% for CTMP, NBSK and Whatman paper and smaller than 6% for the UBSK paper although the uncertainty for different positions of samples are larger due to the non-uniformity of the grammage and the thickness of the samples, as described in section 2.2.1 and Table 2.2. The highest uncertainty of 9% is associated with the UBSK samples and at short wavelengths.

To apply controllable pressure to the samples, different weights are added on the pressure applying rods (Figure 2.1). The rods deliver a force to the glass slides that in turn transmit a fairly uniform pressure to the paper sample. For the zero pressure case the rods are fixed in position to align the glass slides and the paper sample without applying any pressure.

2.2.2.2 Microscopic Imaging

As shown in Figure 2.2, a Nikon® EclipseTM TE2000-U inverted microscope is utilized as the imaging system. The microscope is equipped with several different filter cubes with specific band-pass filters, and the images are recorded using a LaVision® sCMOS camera. This setup captures the total intensity of the transmitted light within the passing spectrum of the filters. The images are captured with an exposure time of 100 *ms*, a frame rate of 2 *Hz* and the full camera resolution of 2560 × 2160 pixels. With a Nikon® CFI 1x objective lens, the field of view is 16 *mm* × 14 *mm* with a spatial resolution of 6.25 $\mu m \times 6.25 \mu m$. To eliminate the effect of fluorescence

contamination at lower wavelengths of excitation, a high-pass UV filter with cutoff wavelength of 400 *nm* is applied to the lamp.

2.2.3 Microscopic Imaging of Moisture Content in Paper

The intensity of the transmitted light captured by the microscopic imaging setup can be used to measure the moisture in paper at high spatial resolution. Knowing the relationship of the moisture content and transmittance, the moisture content at each point of the image (each pixel) can be calculated easily although a spatial averaging over $62.5 \mu m \times 62.5 \mu m$ windows is applied during image processing to account for the typical non-uniformities of paper. The microscopic setup can be independently used for calibration and moisture content measurement in paper however, as can be seen in Figure 2.2, "optical filters" confine the measured wavelength of transmitted light in the microscopic setup.

Figure 2.3 shows a setup to demonstrate the effectiveness of the microscopic method for moisture measurement in paper. Images of a Whatman paper sample are taken at $\Delta t = 0.5 s$ time intervals. The sample is kept dry at the beginning of the experiment and at time t = 0 s water starts being absorbed by the paper from one of its edges, which is immersed in a small water container (Figure 2.3).



Figure 2.3 Schematic of the experimental setup for dynamic moisture mapping in paper.

2.3 Results and Discussion

2.3.1 Spectral Result

Using the spectrographic setup, the relative transmittance spectra of samples with different moisture content are obtained (Figure 2.4). The relative transmittance is defined as the ratio of absolute intensity of transmitted light *I* to the absolute intensity of the reference state I_0 e.g. dry or no mechanical loading. As expected, all curves show that the transmittance increases with increasing moisture content of the paper samples, due to the RI matching of water in the paper. By exciting samples using the monochromator and measuring the fluorescence response in the whole visible spectrum, it is observed that the maximum intensity of fluorescent light is 650 times smaller than the transmitted light when a hardwood sample is excited by violet light ($\lambda = 403 \pm 6 nm$) and emits blue light ($\lambda \approx 420 nm$). Accordingly, autofluorescence produces negligible errors in the measurement of paper transmittance. Detailed studies have been conducted on autofluorescence properties of different types of paper [95–98].

The dependency of the transparency of all bleached samples on the wavelength is negligible, which means the color of the paper samples does not change significantly with moisture content. The bleached samples with 120% moisture content become about three times more transparent compared to the dry cases, which is significant (Figure 2.4a, b and d). On the other hand, the UBSK sample's relative transmittance is reduced with increasing wavelength (Figure 2.4c). Since UBSK is unbleached, a large amount of lignin is present in this sample and its absolute absorbance is a function of wavelength and it is more absorptive at shorter wavelengths. By adding water to the UBSK sample, a color change is apparent and the transmittance changes more for shorter wavelengths; however, the absolute transmittance at shorter wavelengths (blue) remains smaller

than at longer wavelengths (red). The absolute transmittance (the ratio of intensity of transmitted light to the light source intensity I^*) is shown in Figure 2.5 for dry paper samples. As expected, bleached (white) papers have a fairly flat transmittance in the visible spectrum although the brownish color of the UBSK sample implies greater absorbance at shorter wavelengths. To validate the experimental results, the optical transmittance of UBSK samples was measured using a commercial instrument Technidyne® ColorTouch-PCTM. The measured transmittance $T = I/I^* = 0.0296 \pm 0.0001$ over $400 \text{ nm} \le \lambda \le 700 \text{ nm}$ nm showed good agreement with the transmittance (T = 0.028) measured by the experimental setup shown in Figure 2.1.



Figure 2.4 Spectral relative transmittance of paper samples at different moisture contents; a) Hardwood CTMP paper, b) NBSK paper, c) UBSK paper, d) Whatman paper. The typical repeatability corresponds to the typical standard deviation of 10 intensity measurements.



Figure 2.5 Spectral absolute transmittance of dry paper samples.

2.3.2 Relative Transmittance and Moisture Content Relationship

The dependence of the relative transmittance on moisture content can be calculated at different wavelength bounds by integrating the results obtained in section 2.3.1 by averaging over specific wavelength intervals of 50 nm, as illustrated in Figure 2.6. These results are reproduced using the microscope with band-pass filters with identical wavelength bounds. The measurements are done with 20% moisture content steps. In all cases, the results from microscopic imaging are identical to the spectrograph results, validating these results.

Adding more water to the paper eventually saturates the sample by filling all the pores, interstices between fibers and the lumens of the fibers and therefore the additional change in transmittance becomes smaller while the transmittance asymptotically approaches a final value, which reduces the measurement resolution at high moisture content. The saturation regime is illustrated in Figure 2.7 for Whatman paper, where it can be observed that the measurements are

of high sensitivity for moisture content below 120%, and paper is almost saturated for moisture content above 200%. The effect of temperature on transmittance was investigated in the range of 25 °C to 90 °C. The measurements showed a variation of transmittance within the experimental uncertainty for all paper samples (shown in Figure 2.8). By repeating the measurement for thicker paper samples (2 to 5 times the original thickness), it was observed that the absolute transmittance of paper decreased with increasing paper thickness for both dry and wet paper samples, as expected. The thickness of paper does not affect the shape of the calibration curves (e.g., Figure 2.6), but the values of relative transmittance can vary for different thicknesses, which necessitates recalibration if a different paper thickness is studied.



Figure 2.6 Relative transmittance vs moisture content for different paper samples in some wavelength bands; a) Hardwood CTMP paper, b) NBSK paper, c) UBSK paper, d) Whatman paper.(Transmittance was measured at increments of 20% moisture content.)



Figure 2.7 Relative transmittance of Whatman paper up to high moisture content.



Figure 2.8 Variation of transmittance with temperature for Whatman paper for different wavelengths.

2.3.3 Effect of Mechanical Loading

Applying pressure to paper samples can change the transmittance by two different mechanisms. First, applying pressure can change the structure of the paper, decreasing the porosity and changing the distance and arrangement of fibers. Second, trapped water in the narrow space between the external surface of paper and the glass slides act as another RI matching mechanism between the paper and the glass. In the drying section of a typical paper machine an average pressure of 1 - 13 kPa is applied to the paper that is sandwiched between a drying fabric and hot cylindrical heaters [88]. In the current study the effect of an average pressure up to 28 kPa is investigated by applying a weight to the paper samples using the pressure applying rods in the spectrographic measurement setup. It is observed that the effect of pressure on the transmittance of CTMP and Whatman paper is negligible, smaller than the uncertainty of the experiment (3%) even for the highest moisture content case (120%). On the other hand, for a high moisture content in NBSK and UBSK samples, the transmittance increases with pressure, as expected (shown in Figure 2.9). However, the transmittance increase within the range of applied pressure in the drying section of a paper machine is negligible. Consequently, the measurement is insensitive to dryer fabric tension and recalibration is not necessary.



Figure 2.9 Variations of relative transmittance versus pressure for NBSK and UBSK at high moisture content (M) over 600 $nm \le \lambda \le 650 nm$ (sample size: 10 $mm \times 10 mm$)

2.3.4 Wetting Experiments

2.3.4.1 Droplet Experiment

To independently confirm the accuracy of the technique on a paper sample with a large spatial moisture content variation, a small amount of water, with weight corresponding to a uniformly wetted sheet of 25% moisture content, is added to the center of a $14 \text{ }mm \times 14 \text{ }mm$ piece of Whatman paper. The droplet is absorbed swiftly by the paper and starts spreading through it (Figure 2.10). The average moisture content of the sheet is determined using the transmittance measurement technique. Every 50 seconds the sheet is weighed as an independent measure of its moisture content to measure the lost water through evaporation. The results of the average transmittance, nonuniformity of moisture content, and gravimetric measurements are shown in Figure 2.11. The nonuniformity of moisture content is calculated as the standard deviation of

moisture content spatial variations in the paper sheet. The agreement between the two measurements is generally very good, but some points of disagreement require explanation. At the start of the experiment a small amount of water, equivalent to 1% moisture content, is not absorbed into the paper, and this is confirmed by the gravimetric measurement. During the experiment more water (equivalent to 4% moisture) evaporates from the paper but remains in the chamber, condensing on the chamber inner surfaces. Finally, a small amount (equivalent to <1% moisture) leaks from the chamber within $\Delta t = 250 \text{ s}$. It is believed that the condensed vapor on the chamber inner surfaces is responsible for most of the discrepancy between the transmittance and gravimetric measurements. These measurements show that, even with a highly variable spatial distribution of moisture (the standard deviation varies from 25.2% at the start of the experiment to 11.7% at the end), the transmittance technique yields accurate measurements of moisture content. Considering gravimetry as the reference, the measured average moisture using the transmittance technique has an imprecision and inaccuracy of 0.4% and 1.4%, respectively.



Figure 2.10 Moisture content field as a function of time for a Whatman paper sample in a droplet spreading experiment; the field of view is 13 mm by 13 mm and the grey-scale map shows the moisture content percentage (scale-bar length: 2 mm).



Figure 2.11 Average and standard deviation of moisture content of a non-uniformly wetted piece of Whatman paper in a sealed chamber as in Figure 2.10.

2.3.4.2 One-dimensional Wetting

A simple wetting experiment is carried out on a dry rectangular Whatman paper sample that absorbs water from one of its edges. The experiment demonstrates the usefulness of the proposed measuring method for dynamic moisture content measurement in paper. The moisture content is measured based on the calibration curve in Figure 2.6d. Because of fiber-scale non-uniformity of the paper samples, the light intensity is averaged over a 10×10 pixel (62.5 $\mu m \times 62.5 \mu m$) area to reduce the noise.

The wetting process is illustrated in Figure 2.12 as moisture content maps at different times. This wetting process contains two stages: a moving wetting front and saturation. The wetting front is characterized by an abrupt change in the spatial distribution of moisture, which propagates through the paper in about 30 seconds. After the passage of the wetting front, water penetrates into the paper more slowly as the paper moisture content asymptotically approaches saturation. The reduced rate of water uptake is attributable to the reduced capillary forces. The average moisture content of the paper sample (Figure 2.13) increases with time as water penetrates into the paper. In the wetting front stage, the moisture penetrates into the paper with a relatively high and constant speed and increases the average moisture content of the paper linearly with time, as can be seen in Figure 2.13 ($t \le 35 s$). Thereafter, the moisture content asymptotically approaches the saturation value.



experiment; the field of view is 16 mm by 14 mm and the grey scale-maps show the moisture content percentage.



Figure 2.13 Wetting experiment; average moisture content vs. time; typical uncertainty was obtained from transmittance characterization.

2.4 Conclusions

The optical transmittance of paper as a function of moisture content has been investigated for four different types of paper. Refractive Index matching caused by water in the paper pores is responsible for the monotonic increase in the transparency of paper with moisture content. The relation of moisture content and relative transmittance of paper has been characterized using two experimental setups: a) a spectrographic method, for measuring the transmittance at different wavelengths, and b) a microscopic method, for measuring the transmittance and capturing the spatiotemporal moisture content in paper. The results showed that the transmittance of paper can be increased about 3 times by increasing the moisture content from 0% to 120%. The correlation of moisture content and paper relative transmittance, characterized by both experimental setups, was utilized as a novel technique for moisture measurement with high resolution and an

uncertainty of 3-7% (depending on the paper type and wavelength of light) for moisture contents in the range 0% to 120%. The measurements have negligible sensitivity to pressure, for pressures below 10 kPa. As 10 kPa is well above the maximum local pressure present in the dryer section of a typical paper machine, this measurement technique would appear to be highly suitable for moisture measurement in a dryer. Additionally, the effect of temperature on transmittance is negligible in the typical temperature range of cylinder dryers of paper machines.

The accuracy of the transmittance method was measured by observing the transient absorption of water into a sheet. Comparison of the average moisture content measured optically with independent gravimetric measurements showed a 2% discrepancy between the two techniques. A second simple experiment, involving the transient absorption of water by paper, demonstrated the power of the transmittance method. This experiment showed that water absorption by a sample of Whatman paper can be characterized by two stages: rapid progression of a wetting front through the sheet, followed by a slow approach to paper saturation. Apart from its application to paper, this method has potential for the experimental study of fluid diffusion in a variety of other porous media.

Chapter 3: One-Sided Transparency Measurement

3.1 Introduction

In this chapter, a novel technique for one-sided measurement of optical transparency is presented. The technique is evaluated using a microscopic setup to measure the transparency of known neutral density (ND) filters. An optical simulation is also performed to estimate the achievable resolution. The method is then applied to a moisture content (MC) measurement experiment to study the moisture distribution in paper during drying [99, 100].

3.2 Optical Technique and Theory

3.2.1 One-sided access and experimental design and concept

A novel method is described for measuring the transmittance of samples that are optically accessible on only one side. The fundamental concept is to illuminate the sample from one side, Surface 1, and measure the fluorescent response of a fluorescent coating or layer placed on the second side of the medium (Figure 3.1). Consider excitation light, of wavelength λ_e and initial intensity $I_{e,1}$, incident on Surface 1. If the absorbing medium and incoming light are uniform, the intensity of light reaching the fluorescing layer is uniform and given by $I_{e,2} = T_{\lambda_e}I_{e,1}$, where T_{λ_e} is the transmittance of the medium at the wavelength λ_e . This fluorescent material emits light of wavelength λ_f when it is excited by light of wavelength λ_e . The intensity of light emitted by the fluorescing material is a function of the quantum yield (the ratio of the number of photons emitted to the number of photons absorbed), the absorptivity, and the refractive index of the material [101]. The yield of regular fluorescent materials changes linearly with the intensity of the excitation light if the excitation power is lower than the saturation intensity ($I_{f,2} \propto I_{e,2}$) [102]. The emitted fluorescent light then passes back through the sample, along which path a fraction of the light is

absorbed, resulting in an intensity $I_{f,1} = T_{\lambda_f} I_{f,2}$, where T_{λ_f} is the transmittance of the medium at the wavelength λ_f . This light is then captured by collecting optics.

Because the fluorescence response is of longer wavelength than the excitation light (based on Stokes law, $\lambda_e < \lambda_f$), the excitation light and its reflections can be easily removed using an optical filter [103]. Neither the excitation light (λ_e) nor the emitted fluorescent light (λ_f) need necessarily be at a single-wavelength, but rather they may have a band of wavelengths. However, to minimize the effect of reflection from Surface 1 on the transmission measurement, it is preferable that there is negligible overlap between the excitation and emission wavelength bands. The refractive index difference at the interfaces results in light reflection and affects the intensity of transmitted light. The Fresnel reflection coefficient (the fraction of light reflected from the surface), is a function of the angle, polarization, and refractive indices of media. For low emission angles (collimated light normal to the surfaces or low numerical aperture), the reflection coefficient is not a function of light polarization [104], and therefore the polarization of the light has minimal impact on this transmission measurement.



Figure 3.1 Excitation and emission light on different surfaces.

The intensity of the light measured by the collecting optics is then a function of 1) excitation intensity, 2) transmittance of the sample at λ_e , 3) quantum efficiency of fluorescent dye/material, 4) transmittance of the sample at λ_f , and 5) optomechanical design of the setup. By normalizing the results, the effect of excitation light intensity, quantum yield of the fluorophore and the optomechanical design are accounted for and the intensity of the fluorescence response will be a function of the sample's transmittance (as explained in section 3.2.2). Figure 3.2 shows a simple fluorescence microscopy setup for transmittance measurement from one side.



Figure 3.2 The one-side measurement setup.

3.2.2 Effects of Diffuse Illumination and Wavelength Dependency

Consider a semi-opaque thin film illuminated by a collimated light source. The Bouguer-Beer-Lambert law describes the relative intensity of transmitted light:

$$I/I_{i} = (1 - R_{F})\exp(-\mu_{t}D), \qquad (3.1)$$

where I and I_i are the intensity of transmitted and incident light (W/m^2) , respectively. R_F is the Fresnel reflection coefficient which is a function of the refractive index of this film and the surroundings and the angle of the light beam to the surface. *D* is the thickness of the film (*m*), and μ_t is the light extinction coefficient of the film (1/m). The extinction coefficient of the medium is the summation of its absorption coefficient (μ_a) and scattering coefficient (μ_s): $\mu_t = \mu_a + \mu_s$ [104]. The Bouguer-Beer-Lambert law is accurate for highly absorptive media ($\mu_a \gg \mu_s$). In case the collimated light is replaced with a diffuse layer, the light rays won't travel through parallel paths and therefore *D* will vary depending on the path. For the one side measurement, the fluorescent layer acts like a diffuse source and the collecting optics need to be focused on it (Figure 3.3). Therefore, the measured intensity is the summation of the diffused light passed through the medium restricted by the numerical aperture (NA) of the collecting optics. NA is defined as:

$$\alpha = \sin^{-1}(NA/n) \tag{3.2}$$

where α is one-half of the angular aperture and *n* is the refractive index of the imaging medium. The intensity of the collected light can be determined by integrating the total collected light over the angular range of $\Omega = 0$ to $\Omega = \alpha$. Using Equation (3.1), the total collected light is given by:

$$I = \int_0^{\alpha} I_{\Omega,f}(\Omega) (1 - R_F(\Omega)) \exp(-\mu_t \frac{D}{\cos \Omega}) \, d\Omega.$$
(3.3)

where the angular distribution of the emitted light from the fluorescent medium is $I_{\Omega,f}(\Omega)$ and the length of the light trajectory in the sheet is given by $D/\cos \Omega$. The angular distribution of the emitted light is itself a function of the fluorescent material's physical and surface properties. For collimated light, the emission intensity can be defined as $I_{\Omega,f}(\Omega) = I_i \delta(\Omega)$ with the Dirac function $\delta(\Omega)$. This reduces Equation (3.3) to (3.1) regardless of NA.

It should be noted that while collimated light can be used for the excitation, the easiest way is to use a typical fluorescence imaging system such as a fluorescence microscopy setup. Since the excitation light has to pass through the medium, Equation (3.1) or (3.3) should be utilized for the calculation of the excitation intensity for collimated light or a fluorescence imaging setup, respectively. Consequently, the ultimate measured fluorescent light intensity is affected two times by the medium; once for light at the excitation wavelength and once for light at the emission wavelength and it is a function of fluorescence quantum yield and angular diffusivity of the surface. For media that are optically diffuse, the excitation light is also diffused before reaching the fluorescent medium.

For an absorbing medium with negligible wavelength dependency ($T \cong T_e \cong T_f$) and using a fluorescence microscopy setup, the intensity of collected light will be $I_f = I_i K T_e T_f = I_i K T^2$. The coefficient *K* is the ratio of the intensity of measured light to excitation light ($K = I_{f_0}/I_i$) for the case when the sample is completely transparent, and it is a function of the fluorescent medium properties. Hence the transmittance can be calculated as follows:

$$T = \sqrt{I_f / I_{f_0}} \tag{3.4}$$

In case the reference measurement is done without the presence of the sample $(I_{f_0^*})$, the Fresnel reflection of the surfaces should be taken into account. If relative transmittance measurement is the goal (e.g. as described in chapter 2 or reference [105]), I_{f_0} can be replaced with the desired reference provided that the same fluorescence measurement design is used, in order to cancel out the effects of fluorescence quantum yield and diffusivity. In this case the fluorescence response should be linear and not be saturated or affected by photobleaching.

3.2.3 Spatial Resolution

In the one-sided measurement technique, the fluorescent medium plays the role of a noncollimated light source. An important downside of using a non-collimated light source is the reduction in spatial resolution of the measurement in case the medium has spatial non-uniformities that should be resolved. If the medium has spatial absorptivity variations in its plane, using collimated light leads to an accurate mapping of the transparency field while light beams emitted by a non-collimated light source (such as a diffuse fluorescent surface) and collected on the detector have passed through different locations of the medium and therefore are affected by its uneven optical properties (Figure 3.3).

To quantify the importance of this effect, a simplified case can be studied. The medium is assumed to be made of two parts with different absorptivity as illustrated in Figure 3.3. The two parts have the same refractive indices, and there is no gap or optical obstacle at the interface. If collimated light passes through the medium, the intensity of the transmitted light will have a sharp edge at the border of two parts. However, using a diffuse light source, causes the captured intensity near the interface to vary smoothly. Figure 3.3c shows that a higher NA causes a more significant decrease in resolution as the collection angle α grows with the numerical aperture (Equation (3.2)). Additionally, by increasing the thickness *D*, the diverging light rays pass through a longer distance in the plane of measurement, which increases the effect of spatial variations and lowers the resolution. The actual length affected by the interface

$$x_0 = 2D \tan(\alpha) \tag{3-5}$$

depends on the sample thickness and the acceptance angle of the optics. For the thickness D = 1 mm and different numerical apertures NA = 0.3 and NA = 0.04 (corresponding to 10x and 1x Nikon® objective lenses), the smoothed profile spreads up to $x_0 = 408 \mu m$ and $x_0 = 53 \mu m$, respectively. A light tracking simulation was carried out to verify these calculations and the results were in perfect agreement. The normalized light intensity profiles for different numerical apertures are sketched in Figure 3.4.

It must be noted that since with a non-collimated light source some light rays pass longer distances in the medium, the measured absorptivity will be slightly higher. This difference is a function of the NA, absorptivity of the medium and angular diffusivity of the emitting material. For instance, by using an objective lens with NA = 0.04, the measured absorptivity of a ND2 filter illuminated by a diffuse light source will be measured to be 0.01% higher than its true value.



Figure 3.3 Effect of spatial non-uniformities on the measured transmittance using a) collimated light, b) noncollimated light and the collecting optics with NA = 0.3 and n = 1.5, and c) the schematic of collecting optics for non-collimated illumination.



Figure 3.4 Normalized light intensity profiles for different numerical apertures. The thickness of the obstacle is D = 1 mm and the light source is assumed to be diffuse.

3.3 Experimental Implementation

As illustrated in Figure 3.5, a Nikon® EclipseTM TE2000-U inverted microscope is utilized for fluorescence imaging. Using proper optical filters (standard Di-8-ANEPPS filter cube), blue light (460 $nm < \lambda_e < 500 nm$) is used to excite the fluorescent material and the red emission response (575 $nm < \lambda_f < 640 nm$) is measured by the sCMOS camera. The fluorescent material is the RenolTM Red pigment by Clariant® masterbatch (polyethylene terephthalate carrier). Using a CFI Plan UW 1x objective lens, the field of view of the recording is 16 mm by 14 mm.



Figure 3.5 The schematic of moisture content measurement setup (the scale bar on the fabric photo is 5 mm long).

3.3.1 ND Filters Transmittance Measurement

One of the most important differences of the one-side measurement method is that the passed light has different wavelengths of excitation and emission. Therefore, the wavelength dependency of the medium's absorptivity affects the final result and the measured transmittance is equal to the geometric mean of transmittance at λ_e and λ_f , as described in section 3.2.2. To quantify the accuracy of the method, it was employed to measure the transparency of four neutral density filters, ND2, ND4, ND8, and ND16 which reduce the intensity of passed light by a factor of approximately 2, 4, 8, and 16, respectively. The experiments were conducted with a 1x objective lens with NA =0.04. Transparent glass of the same refractive index as the ND filters was used to measure the reference intensity I_{f_0} . Then Equation (3.4) was employed to calculate the transmittance of the filters $T_{one-sided}$. Using a low NA optical system and clear glass for the reference measurement minimizes the measurement error and the effect of interface reflections. The spectral transmittance of the filters was independently measured using a conventional spectrographic setup (Figure 3.6). Table 3.1 compares the transmittance measured by the spectrographic and one-sided measurement techniques. Using the transmittance at the excitation (T_e) and emission (T_f) wavelengths, the expected value for transmittance with one-sided method can be calculated as $T_{e-f} = (T_e T_f)^{1/2}$. The average error of the one-sided measurement was 0.6% with a RMS error of 1.5%. The maximum error of the measured absolute transmittance was 2.4%.



Figure 3.6 Spectral transmittance of the ND filters in visible spectrum.

Table 3.1 Results of the spectrographic and one-sided measurement techniques for four ND filters.

| ND | Spectrographic Measurement | | | One-sided Measurement | Relative | |
|--------|----------------------------|------------|-----------|-----------------------|----------------|-----------|
| Filter | Optical Density | $T_e~(\%)$ | T_f (%) | T_{e-f} (%) | Tone-sided (%) | Error (%) |
| ND2 | 0.30 | 51.6 | 50.3 | 50.8 | 50.0 | 1.50 |
| ND4 | 0.59 | 25.7 | 25.4 | 25.6 | 25.7 | -0.43 |
| ND8 | 0.91 | 12.5 | 11.9 | 12.2 | 12.4 | -1.22 |
| ND16 | 1.20 | 6.40 | 6.22 | 6.31 | 6.16 | 2.36 |
3.3.2 Moisture Content Measurement in Paper Drying

3.3.2.1 Experiment Methods and Materials

As an example of the validity of the one-sided transmittance measurement technique, it was used to measure the spatial variation of paper moisture content during drying. In conventional paper machines, paper is dried by sandwiching it between a porous dryer fabric and a heated metal cylinder. Traditional paper drying measurement methods neither provide enough resolution and accuracy nor are functional while the paper is sandwiched between the drying cylinder and fabric (section 1.2).

The relationship between the moisture content of paper and its transmittance was characterized using spectrographic and microscopic methods by measuring the transmittance of uniformly wet paper with a known moisture content as described in chapter 2. The moisture content of paper has a monotonic relationship with the optical transmittance and therefore the moisture content can be inferred from measurements of the transmittance (as described in section 2.3). To study paper drying, one-sided optical access to the sample was achieved by replacing the hot cylinder surface with a transparent indium tin oxide (ITO) heater on a glass substrate. The ITO heater is made of glass coated with a thin layer of electrically conductive material. The temperature of the ITO heater can be controlled accurately using temperature sensors and a PID controller to control the electrical current. The remaining requirement of the one-sided transmittance measurement is the presence of a fluorescent material on the blocked side of the medium. Fluorescence can be produced by coating the dryer fabric with a fluorescent material and some of the commercially available fabrics are made with auto-fluorescent polymers, which makes coating unnecessary. In this study, an autofluorescent fabric was used for the experiment. General Electric® Whatman™ grade 1 chromatography paper is chosen for the experiments. This paper, which is the world standard

chromatography paper, contains pure cellulose produced from cotton linters with no additives. The grammage and thickness of Whatman paper are $87g/m^2 \pm 2\%$ and $173 \mu m \pm 2\%$, respectively. Spectrographic measurements showed that the wavelength dependency of Whatman® paper's transmittance is negligible in the visible spectrum (section 2.3).

As shown in Figure 3.5, the paper sample (22 $mm \times 22 mm$) is fixed between the ITO heater and a dryer fabric. Water is added to dry paper to bring its initial moisture content to 130% (mass of water over mass of dry paper). A mechanical mechanism applies a uniform average pressure of 2 kPa to the fabric. The fabric type is a commercially available dryer fabric (MagnaTecTM) produced by AstenJohnson Inc. (Figure 3.5). To make drying conditions as realistic as possible, the temperature of the ITO is set at 90°C, which is the average surface temperature of cylinders in typical paper machines. The psychometric conditions of air are fixed at $T_{Air} = 60$ °C and a relative humidity of 70% as the average conditions of a typical paper machine [89, 106]. At the beginning of the experiment the ITO heater suddenly turns on and the surface temperature reaches the set point temperature in less than 3 seconds. The experiment continues until the paper sample becomes bone-dry (MC = 0%). An image processing code reads the captured data and generates the map of moisture content using a unique calibration for every measuring window, as described in chapter 2.

3.3.2.2 Results

The measured variation of average moisture content with time is shown in Figure 3.7. Two stages of drying are obvious in the drying curve which is consistent with the literature [88]. In the first stage (0-10 seconds in Figure 3.7) involves the evaporation of the free water that fills the pores and the lumen of fibers. The second stage, with lower drying rate is associated with the drying of imbibed water that is stored within the swollen cell walls of the fibers. The structure of the dryer

fabric is shown in Figure 3.8(a). This contour image was generated using a three-dimensional image of the fabric captured by a Thorlabs® TELESTOTM-II Spectral Domain OCT device. The working principal of OCT is described in reference [107]. The spatial resolution of this measurement is 5 μ m. Maps of moisture content at different times are illustrated in Figure 3.8b-f. The pattern of moisture content within the paper during the drying is correlated with the fabric structure. The cross-correlation between the surface elevation and the paper moisture distribution is initially r = 0 (at t = 0, when the paper is uniformly wet). It then rises to a maximum of R = 0.433 at t = 5s, part way through the drying process. Finally, the cross-correlation between fabric structure and local paper drying rate is that the fabric is impermeable. The fabric material traps water in the paper at the contact points, slowing drying at these regions.



Figure 3.7 The average moisture content as a function of time. The drying conditions are set at the reference conditions defined in section 3.3.2.1.



Figure 3.8 The structure of the dryer fabric and the contours of moisture content in paper at different times during the drying (field of view is 7.50 *mm* by 5.50 *mm*)

3.4 Conclusions

A novel method for one-sided optical transparency measurement of thin films has been developed. To measure the transmittance from one side, the excitation light of wavelength λ_e illuminates the optically accessible side of the film, passes through the film, and excites fluorescent material that is present on the other side of the film. The fluorescent layer absorbs the excitation light and fluoresces. The emitted light passes back through the object and is then captured by the collecting optics. The intensity of the captured light is a function of the object transparency at both wavelengths and the optical system characteristics, the latter of which can be easily normalized.

Since the fluorescent layer produces non-collimated light, the spatial resolution of the measurement will be lower than for a traditional measurement with collimated light. For instance, for a 1 mm thick object with a step spatial change in transmissivity, imaged with NA = 0.04 optics and the one-sided optical transparency measurement technique, shows a smoothed profile of transmissivity where smoothing of the boundary occurs over a distance of 53 μm .

The accuracy and validity of the technique have been investigated experimentally. To study the accuracy, the transmittance of four known ND filters were measured by this new technique. The average and RMS error in these measurements was 0.6% and 1.5%, respectively. As an illustration of the utility of this technique, the drying of paper sandwiched between a heater and a dryer fabric was studied. Spatiotemporal moisture content maps with high spatial resolution were measured. These maps showed that the local drying rate is affected by the fabric topography.

Chapter 4: Effect of Dryer Fabric

4.1 Introduction

In this chapter the effect of drying variables and fabric structure on the drying rate is investigated. The novel optical technique, described in previous chapters, is employed to measure the spatial distribution of the moisture content of the paper during drying as a function of time, as it is sandwiched between the dryer fabric and a heated surface. Effect of dryer section conditions i.e. psychrometric properties of air, fabric tension, and heater surface temperature on the drying is investigated. Ten commercially available fabrics were studied and their three-dimensional structure was measured using OCT. These fabrics were tested in a custom experimental setup that mimics conditions in a typical paper machine. It is observed that the fabric structure affects the drying rate at different moisture contents differently. Results and discussion section provides key results from the experiments and associated discussion, and the chapter closes with some conclusions, including recommendations for the appropriate selection of papermaking fabrics [108].

4.2 Materials and Methods

4.2.1 Measurement Technique

Typically, in the drying section, the moisture content of paper varies from $MC \approx 130\%$ to $MC \lesssim 8\%$ [1]. In this range, the optical transparency of regular papers (e.g. copy paper, newsprint paper, paper towel, tissue) has a monotonic relationship with its moisture content, which can be easily characterized as described in section 2.3. To determine the transmittance of paper while it is sandwiched between a dryer fabric and a heater, a one-sided transparency measurement technique is employed (chapter 3). By replacing the metal surface of a real dryer cylinder with a transparent heater made of ITO coated glass, one-sided optical access to the paper can be attained as described 56

in chapter 3. To complete the one-sided measurement system, the dryer fabric must be fluorescent (section 3.2). The dryer fabric used in the drying section can either be made of an auto-fluorescent polymer or be coated with an appropriate fluorescent dye.

To measure paper moisture content during drying, collimated light at the wavelength λ_e is directed through the ITO (Figure 4.1). Some of this light passes through the paper, and excites the fluorescent fabric. Then, at an intensity dependent on the fluorescent yield of the fabric, light at the fluorescence wavelength λ_f is emitted by the fabric and passes back through the paper and the ITO, where it is collected using an imaging system. An optical filter is used in the imaging system to filter out all but light at the fluorescence wavelength (thus removing the effects of direct light reflection from the paper). The collected light is proportional to the sample transmittance, and thus directly related to the paper moisture content (section 3.2).



Figure 4.1 Schematic of one-sided optical measurement with the dryer fabric as the fluorescent layer. I and λ are the light intensity and wavelength, and e and f indices represent emission and fluorescence, respectively. (The paper thickness is exaggerated)

4.2.2 Experimental Apparatus

An apparatus was designed to simulate conditions in a typical multi-cylinder dryer (Figure 4.2a). A Fuji® VFC400P regenerative blower circulates air in the system. A specially designed test section, with a cross section of 56 mm by 20 mm, is used to generate uniform air flow over the fabric, analogous to that experienced when a fabric and paper web move at high speed through a dryer hood. The test section characteristics, including the dimensions, mesh and honeycomb, are selected based on the information provided in reference [109]. The blower can generate a maximum speed of 18 m/s in the test section. A wet sample of paper is placed on the (initially cold) ITO heater, which provides a 22 mm \times 20 mm transparent window on the bottom of the test section (Figure 4.2b and Figure 4.2c). The fabric is placed over the paper and a mechanism applies a pressure of to the fabric, which is a typical pressure used in the industry to press the fabric against the paper web [1, 5]. To make the flow over the fabric even and unidirectional, the air passes through a set of screens and a honeycomb before reaching the test section. A Dantec® 54T42 miniCTATM hotwire is installed in the channel to quantify the non-uniformity and fluctuations of the flow across the channel. Additionally, a Pitot-tube measuring the air velocity five millimeters above the downstream edge of the fabric provides extra information used as an indicator of the average velocity above the sample that is characterized by the miniCTA.

Two proportional-integral-derivative (PID) controllers maintain the psychrometric properties of air at a desired set-point. The temperature and RH of the air are measured by an RH sensor and thermocouples exposed directly to the flow. These values are fed to the PIDs to control the air heater and steam generator and they are used to calculate the air density, which is required to interpret the anemometer results. Another PID controller sets the temperature of the ITO by altering the supply voltage. The ITO temperature is inferred from its electrical resistance, which is a monotonic function of its average temperature. The functional dependence of electrical resistance on temperature was characterized empirically. A water-jacket heat exchanger reduces the air temperature after the measurement section to avoid exceeding the safe operating temperature of 65°C at the pump inlet.

As explained in section 3.3, a Nikon® Eclipse[™] TE2000-U inverted microscope, a standard Di-8-ANEPPS filter cube, and a CFI Plan UW 1x objective lens are employed as the fluorescence imaging system. The fluorescent material of the dryer fabrics is Renol Red[™] pigment by Clariant® masterbatch (polyethylene terephthalate carrier). General Electric® Whatman[™] grade 1 chromatography paper is the paper type used for the experiments. The grammage and thickness of Whatman paper are presented in Table 2.2. It has been shown that the wavelength dependency of the relative transmittance of Whatman paper is negligible in the visible spectrum (section 2.3).



Figure 4.2 Schematic of the experimental apparatus, b) top view picture of the test section, and c) cross section of the test section

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4.2.3 Fabric Types

Ten commercially available fabrics, manufactured by AstenJohnson Inc., are used in the experiments. The three-dimensional structure of each fabric is scanned by a Thorlabs® TELESTO[™]-II Spectral Domain OCT device. An image processing code reads the raw recorded data and generates orthogonal views of the fabric structure (Figure 4.3). The spatial resolution of this measurement is 14 μm in the fabric plane and 4 μm in depth. As illustrated in Figure 4.3, fabrics can be categorized in two groups: Type-A, flat fabrics (MagnaTecTM fabrics shown in Figure 4.3a-e); and type-B, non-flat fabrics (MRT[™] and SpiralFine[™] fabrics shown in Figure 4.3f-j) can be distinguished by the geometry of their machine direction filaments. Fabrics F1-F9 are made of flat monofilaments with rectangular cross sections, whereas the surface of fabric F10 is made of cylindrical monofilaments. The three-dimensional fabric geometry maps generated by the OCT are used to quantify the geometric characteristics of the dryer fabrics. Both the "contact area" and the "covered area" are shown in Table 4.1. The contact area is the portion of the surface area of the paper where the paper and fabric are believed to be in physical contact, while the covered area is the portion of the surface area of the paper in which the distance between the paper surface and the topmost surface of the fabric is smaller than a value h. The covered area at a distance h_1 , corresponds to the combined area of the fabric topology with $0 \le h \le h_1$. Independently, each fabric was placed on Fujifilm® Extreme Low pressure (4LW) films and an even mechanical pressure was applied to the non-contacting side of the fabric. The surface of the fabrics was coated by a color-forming agent that reacts with the color-developing layer of the films once they contact each other. This makes the contact area measurement possible at contact and under low pressure as in a typical papermachine. The films were digitally scanned to calculate the contact area of the fabrics. The calculated contact area with this technique was equal to the covered

area calculated at $h = 35 \ \mu m$ using the OCT measurements. The covered area is related to the contact area of the fabrics, but it is a unique function of *h* for each fabric. The air permeabilities of the fabrics, as measured by the manufacturer, are also presented in Table 4.1. The values in the table are the superficial speed of standard temperature and pressure air through the fabrics when driven by a pressure difference of 125 *Pa*. The surface properties of all fabrics (e.g. water-air interface contact angle) are identical as they are fabricated with the same polymer material with no microscale surface features.



d) F4

e) F5





h) F8



Figure 4.3 Orthogonal views of different fabrics captured by OCT. The surface field of view is 9 mm by 9 mm and the depth is 2 mm. The machine direction (MD) and cross machine direction (CD) is identical for all fabrics.

| ID | Туре | Commercial Name | Contact Area (%) | Covered Area (%), $h = 130 \ \mu m$ | Permeability (m ³ /m ² h) |
|-----|------|---------------------------|---------------------|--|--|
| F1 | А | MRT-HS8 | 33.4 | 53.1 | 2325 |
| F2 | А | MRT-HS4 | 40.1 | 47.3 | 2480 |
| F3 | А | MRT-51 | 50.2 | 71.0 | 2325 |
| F4 | А | MRT-71 | 75.0 | 82.2 | 2325 |
| F5 | А | H3-AJ603 | 56.2 | 63.2 | 2325 |
| F6 | В | MagnaTec 3/1 | 22.5 | 41.0 | 1705 |
| F7 | В | MagnaTec-II 3/1 | 25.0 | 45.4 | 2790 |
| F8 | В | MagnaTec-II 2/1 | 21.2 | 31.0 | 5890 |
| F9 | В | MagnaTec-II PairedWrap | 17.0 | 26.2 | 2325 |
| F10 | В | SpiralFine | 30.8 | 38.3 | 1705 |

Table 4.1 Commercial name, contact and covered area from the OCT measurements, and air permeability of the dryer fabrics at 125 *Pa*, as provided by the manufacturer.

4.2.4 Experimental Procedure

Initially, a precise micropipette is used to add water to dry paper until the moisture content reaches MC = 130%. The wet paper is kept in a sealed chamber for five minutes before the experiment to let the paper equilibrate and the moisture distribution to become even. Afterwards, the sample is sandwiched between the ITO heater and the dryer fabric (Figure 4.2) and the drying process begins by turning a three-way valve to direct the air flow into the test section and simultaneously starting the ITO heater. It takes less than 6 seconds for the flow and 4 seconds for the surface temperature to reach their set-points and stabilize. The experiment continues until the paper sample becomes bone-dry (MC = 0%). During the experiment, the fluorescent imaging system records the light intensity maps with the exposure time of $dt = 100 \, ms$. An image processing code reads the

captured data and generates the map of moisture content using a unique calibration for every measuring window, as described in chapter 2 and chapter 3.

The effect of fabric structure on drying is studied at realistic conditions of a typical paper machine, defined here as "reference conditions". The air speed is set at U = 15 m/s and the temperature and relative humidity of air are fixed at $T_{Air} = 60$ °C and RH = 70%, respectively. The set-point temperature of the ITO is adjusted to 90°C, which is the average surface temperature of drying cylinders in typical paper machines [1, 89]. To study the uncertainty of the experiments, all experiments were repeated more than three times. It was observed that the uncertainty of the measured moisture content at any instant in time is always less than 2.8% for twelve experimental trials under reference conditions. The non-uniformity of the paper grammage and thickness is responsible for a portion of the observed uncertainty.

4.3 **Results and Discussion**

The main objective of this chapter is to assess the effect of fabric structure of paper drying. The effect of other variables (air properties, fabric tension, heater temperature, etc.) on the drying process is also studied in section 4.3.3.

4.3.1 Impact of Drying Conditions

Using the experimental apparatus, described in section 4.2.2, the effect of drying conditions (air temperature, air relative humidity and relative speed, heater surface temperature and fabric tension) on the drying process are investigated. The achievable range and uncertainty of each variable is presented in Table 4.2. To study the effect of the drying conditions, the drying experiments are carried out starting out with a reference condition and fabric (F6) and then altering each variable in turn. In the post processing stage, drying time, trend of drying and spatial variation of moisture content in the paper sheet are compared as indicators of drying efficiency and quality.

 Table 4.2 Achievable range of variables in the experimental apparatus.

| Parameter | Minimum | Reference | Maximum | Uncertainty (at reference conditions) |
|---|--------------------|-----------|---------|--|
| Air temperature (°C) | 35.0 | 70.0 | 80.0 | ±1.5% |
| Air relative humidity (%) (at 70 °C) | 12.0 | 60.0 | 80.0 | ±2.3% |
| Air absolute humidity (kg/kg) | 0.0239 | 0.1409 | 0.2032 | ±2.2% |
| Air speed over the fabric (m/s) | 0.0 | 15.0 | 18.0 | ±7.8% |
| ITO surface temperature (°C) | ~23.0 (ITO off) | 90.0 | 100.0 | ±1.9% |
| Average fabric tension (kN/m) | 0.5 | 2.0 | 6.0 | ±3.0% |



Figure 4.4 Example of the time variation of the measured variables at the reference set-point. The dashed lines show the set points of each variable. The uncertainty values are presented in Table 4.2.

As shown in Table 4.3, the results of experiments are in excellent agreement with the results of other researchers [1, 5, 27, 89]. Specifically, the psychrometric properties of air has negligible impact on the second phase of drying (defined in section 1.1) since the difference in the results for different air temperatures $35^{\circ}C \le T_{Air} \le 80^{\circ}C$ and relative humidities $12\% \le RH_{Air} \le 80\%$ is not statistically significant. Likewise, the speed of air flow over the fabric, which represents the paper-fabric speed, has negligible effect in the range of this study $(V_{Air} \le 18 m/s)$ as the conductive heat transfer (from the heater) has the dominant impact. However, the surface temperature affects the drying significantly. As illustrated in Figure 4.5, drying is dramatically faster at higher heater surface (ITO surface) temperatures. The drying time, defined as the time it takes to reduce the moisture content to MC = 8%, decreases logarithmically with surface temperature (Figure 4.6). This proves that conduction is the dominant mechanism of heat transfer, which is in agreement with the theoretical analysis provided in references [1, 5]. Due to the strong impact of heat transfer efficiency on the drying rate, drying rate is sensitive to the contact resistance of the paper and heater surface. This contact resistance is a function of the fabric tension [1, 5, 26, 27]. By increasing the average mechanical pressure of the fabric from 2 kPa to 6 kPa, the drying time decreases by 5.2%. Studies have shown that increasing the fabric tension may increase the drying rate by up to 50% under specific conditions, although a 7% increase has been reported at the conditions close to the current study [26, 27]. It should be noted that increasing the dryer fabric tension is not possible in most cases since it decreases the production quality and increases the mechanical complexity of the dryer cylinder drives [1].

Table 4.3 Effect of drying conditions on the drying time in the current thesis and the literature.

| | Current thesis | | Previous studies | | |
|---|-------------------|--|-------------------|--|-------------------|
| Parameter | Range of Study | Observed Effect | Range of Study | Reported Effect | Ref. |
| Air temperature (°C) | 35.0 - 80.0 | Negligible* | 70.0 - 140.0 | Negligible* | [1, 5] |
| Air relative humidity (%) (at 70 °C) | 12.0 - 80.0 | Negligible* | 23.0 - 98.0 | Negligible* | [1, 5] |
| Air speed at over the fabric (m/s) | 0.0 - 18.0 | Negligible* | 4.0 - 20.0 | Negligible* | [1, 5] |
| Average fabric tension (kN/m) | 2.0-6.0 | 5.2% decrease in drying time (2 to 6 kN/m) | 1.5 - 5.8 | 7% decrease in drying time (2 to 5.8 kN/m) | [1, 5, 26, 27] |

*Negligible: No statistically significant effect observed



Figure 4.5 Average moisture content vs. time at different heater temperatures. The horizontal dotted line shows the drying time threshold (MC = 8%). All drying conditions at the reference values given in Table 4.2, except for the ITO temperature.



Figure 4.6 Drying time of the paper vs. surface temperature (data extracted from Figure 4.5)

4.3.2 Trends of Drying – Type A and Type B Fabrics

The variation of MC over time for all fabrics is illustrated in Figure 4.7. For all cases, the drying begins with a rapid and relatively steady drop of MC versus time. As the paper becomes dryer, the thermal conductivity of the web drops and the thermal contact resistance between the paper and heater increases, producing a dramatic reduction in drying rate at low moisture content [1, 5]. The MC corresponding to this transition between rapid drying and slower drying is called the critical moisture content (CMC) [1]. At the CMC, most free water (the water between the fibers and macropores) is removed from the paper web and the remaining moisture is the bound water stored in micropores, cell walls and lumens of fibers, which is more difficult to remove [1]. For all dryer fabrics, the mean CMC value is measured to be $\overline{CMC} = 43\%$ with a standard deviation of 7%. CMC showed no correlation with permeability and geometric properties of the fabric. This value

of CMC and its lack of dependence on the fabric structure is consistent with the results of other researchers on paper with the same grammage [1, 110, 111].

A remarkable similarity can be observed in the trend of the drying among fabrics of each type, however, type-A and type-B fabrics show quite different drying trends. The similarity of drying trend correlates with the structural similarities among the fabrics of each group (i.e. filament geometry, contact area etc.), which is the main reason for this categorization. To make the comparison easier, the MC over time of a fabric of type-A and type-B is sketched in Figure 4.8. It can be seen that type-A fabrics have a lower drying rate at high moisture contents ($MC \ge 15\%$) although their drying rate at low moisture contents is significantly higher than type-B fabrics. The drying rate as a function of moisture content for both fabric types is sketched in Figure 4.9. It can be seen, at low moisture contents ($MC \le 15\%$), the drying rate drops faster for type-B fabrics that makes excessive drying longer than the other fabric type. The trend difference between the two types of fabrics has no relationship with the permeability since type-B fabrics (Table 4.1). In agreement with a previous study [5], there is not a statistically significant correlation between the drying time at high or low MC and the permeability of the fabrics.



Figure 4.7 The average moisture content as a function of time during the drying for a) type-A fabrics (F1-F5) and b) type-B fabrics (F6-F10). The horizontal dotted line shows the excessive drying stage threshold ($MC \le 8\%$).



Figure 4.8 Difference in the drying trend of type-A (F3) and type-B (F6) fabrics. The horizontal dotted line shows the excessive drying stage threshold ($MC \le 8\%$).



Figure 4.9 The drying rate as a function of moisture content for a) type-A fabrics (F1-F5) and b) type-B fabrics (F6-F10).

4.3.3 Effect of Fabric Structure on Regular Drying

To study the drying efficiency in realistic conditions on typical machines, "regular drying time", or simply "drying time" is defined as the time required for the MC to drop from 130% to 8%. We

define the "excessive drying time" as the time required for the MC to decrease from 8% to 0%. Under the same mechanical loading, a larger contact area reduces the pressure over the paper and impacts the heat transfer and surface quality of the product [88]. As illustrated in Figure 4.10a, the drying time increases almost linearly with the covered area. The drying rate has the strongest correlation with covered area at the depth of $h = 130 \,\mu m$ from the surface plane of the fabric. There exists a similar, but statistically weaker, correlation of drying time with the contact area of the fabric (Figure 4.10b), with longer drying times corresponding with increased contact area. This observation seems to contradict the widely accepted idea that improvement of the heat transfer results when the contact between the paper and the dryer roll is more uniform [88].

The arrangement of filaments in the dryer fabric can change the geometry of the covered regions. The overlap of nearby filaments results in wider covered spots which makes the minimum distance to an uncovered area longer. This means water must travel a longer distance laterally to reach an area that is open to the air for evaporation. Due to the low lateral diffusion coefficient in the paper plane, explained in section 1.3.1, lateral water transport is relatively slow compared to the time scale of drying [87, 112]. As shown in Figure 4.10a, fabric F4 requires a longer drying time than the value expected if only the overall covered area is taken into account. The adjacent of the fabric F4 filaments in CD direction (Figure 4.3d) results in larger covered spots compared to other fabrics with a similar covered area (e.g., fabric F1). The large gap between the nearby filaments in fabric F5 relative to fabric F1, for instance, results in smaller blocked spots and increases the overall drying rate. The implication of this finding is that, in addition to the covered area, other geometric characteristics such as the shape of the covered spots have a small impact on the drying rate.



Figure 4.10 The drying time (moisture content variation from 130% to 8%) versus a) covered area at $h = 130 \ \mu m$, and b) the contact area.

4.3.4 Effect of Fabric Structure on Excessive Drying

As illustrated in Figure 4.7 and Figure 4.8, the decrease of the drying rate is significantly larger for type-B fabrics when the moisture content falls below 8%. It is observed that the excessive drying time has an approximately inverse relationship with the contact area of the fabrics (Figure 4.11), which suggests that conductive heat transfer has the dominant impact on the drying efficiency in excessive drying (Figure 4.12). The effect of fabric structure on excessive drying is very high – different dryer fabrics can have excessive drying times that differ by a factor of seven (e.g., fabric F5 versus F9). Therefore, if excessive drying is required, fabrics with larger contact area are desirable, particularly in the last run of the drying section. However, fabrics with extremely high contact area and a compact filament arrangement (e.g. fabric F4) have larger blocked spots that may be responsible for relatively slower excessive drying.



Figure 4.11 The excessive drying time (from MC = 8% to bone-dry) versus contact area.



Figure 4.12 Schematic of type-A and type-B fabrics and their dominant impact on the evaporation and contact heat resistance at high and low moisture content. The machine direction is horizontal. (The drawing is not to scale.)

4.3.5 Condensation and Rewetting

During the drying process, water vapor escapes through the dryer fabric. Part of the vapor condenses on the fabric filaments and forms droplets. Once a droplet close to the surface of the paper grows enough to contact the paper, it gets reabsorbed into the paper and forms a small wet region in the paper (Figure 4.13). This phenomenon is captured as transient wet spots for all fabric types, however, the position of these spots is a function of the fabric geometry. It is observed that reabsorption always happens at the edges of the contact points, perpendicular to the filament curvature. The size of the droplets is observed to be proportional to the filament width and the geometry of weaves as wider filaments result in larger rewetted spots. Rewetted spots are first observed when the average moisture content is below MC = 55% and cease when the average

moisture content reaches MC = 5%. Every droplet increases the average moisture content locally by $MC \leq 10\%$ in a spot with diameter $d \leq 1.5 mm$. The number of rewetted spots during the drying process, on average, is $\dot{n} \approx 0.16 \ \#/mm^2$, however, for different fabrics, it varies from $\dot{n} \approx$ $0.05 \ \#/mm^2$ to $\dot{n} \approx 0.27 \ \#/mm^2$ showing no correlation with the geometric properties. Higher RH should result in more condensation and thus an increase in the number of rewetted spots. However, in realistic papermachine conditions, the fabric is not constantly in contact with the paper and accumulated condensate may be removed from the fabric either by the centrifugal force induced by the rotation of the cylinders or by droplet drying that occurs from the fabric as it passes through the open draw. Due to the small number and size of rewetting droplets, this phenomenon does not affect the overall drying rate significantly; the cumulative amount of returned moisture during the drying process is less than 3%. In a real dryer, the fabric is preheated through exposure to the surrounding air. This preheating should reduce the condensation and rewetting.



Figure 4.13 a) The structure of fabric F3, b-f) the contours of moisture content in paper at different times during the drying (field of view is 16 mm by 14 mm and the cross shows the rewetting spot on the fabric structure). One rewetted spot appears at t = 17.5 s and evaporates again in one second.

4.4 Conclusions

The effect of dryer fabric structure on drying has been studied using an experimental apparatus designed to simulate realistic conditions on regular paper machines. A novel measurement technique has been used to investigate the effect of the dryer fabric characteristics on the drying process. Ten commercially available fabrics with different geometrical properties are studied. The fabrics are chosen to cover a large range of structural characteristics and permeability. Although the drying trend shows no statistically significant correlation with the air permeability of the

fabrics, the geometric properties of the fabrics affect the drying trend significantly. Fabrics with flat filaments (type-A) provide faster drying at low moisture contents. Fabrics with non-flat filaments (type-B), on the other hand, have a faster drying rate at high moisture content levels. Evaporation blockage and poor thermal contact are believed to have dominant impact on the drying rate at high and low moisture content levels, respectively. The drying time during regular drying, at high moisture content range, increases linearly with the covered area of the fabrics. In contrast, for the drying regime at low moisture content, the drying rate decreases with the covered area. The arrangement of the filaments is also observed to impact the drying rate; where filaments are adjacent, resulting in larger covered areas of the paper, the drying rate is considerably reduced.

For regular drying, a drying fabric with a non-flat structure, minimal covered area, and only small contiguous covered areas is optimal. If lower paper moisture contents are required, it is recommended that the final section(s) of the dryer be fitted with flat fabrics with large contact areas to optimize the drying efficiency.

Chapter 5: Through Air Drying (TAD)

5.1 Introduction

This chapter focuses on the study of the effect of the dryer fabric, air flowrate and temperature on the drying of paper in TAD. The developed optical method is used to measure the moisture content of paper with high spatiotemporal resolution. Four commercially available fabrics with different permeabilities and structures are studied. The three-dimensional structure of the fabrics is measured using OCT in order to obtain the structural properties of the fabrics i.e. contact area and the geometry of contact spots. A custom experimental setup is designed and built to apply and monitor different drying conditions during the through air drying process. Moisture content, temperature and pressure drop are measured during the experiments as the main parameters that define the drying efficiency. Spatial maps of the moisture content were compared with the local grammage of the paper, to assess if there exists a correlation between the spatial pattern of drying and the grammage distribution of the paper. Section 5.2 describes the experimental setup and procedure. The key results of the experiments are discussed in section 5.3 and the chapter ends with conclusions.

5.2 Materials and Methods

5.2.1 Measurement Technique

To quantify the moisture content in TAD, same measurement principal, defined in chapter 2, can be used. Since TAD fabrics are translucent, there is no need for the one-sided measurement method, however, the fabric's transparency contributes to the total measured transparency, which can be addressed by individually calibrating paper-fabric systems for different moisture contents. It should be noted that the absolute transparency of the fabric can be mathematically taken into account to calculate the resultant paper-fabric transparency. However, this approach may result in lower accuracy due to the effects of the paper-fabric interface and light divergence. More information on the effect of non-collimated light on transparency measurement is provided in section 3.2.2. In this study, the paper-fabric system is calibrated using gravimetric measurement using a precise balance with less than 0.2% uncertainty, as described in section 2.2.

To measure moisture content during drying, collimated light with intensity $I_0(\lambda)$ illuminates the dryer fabric as sketched in Figure 5.1. The transmitted light through the fabric illuminates the paper, passes through the paper and is measured using a sensitive camera. The intensity of the transmitted light $I(\lambda)$ is a function of the fabric's transparency as well as the optical transmittance of paper. To eliminate any interference of autofluorescence and color change caused by the paper or fabric, an appropriate optical filter is employed to filter the measured light, although these effects can also be calibrated out, as described in sections 2.3 and 3.3. Using a microscope setup it is shown that the optical transparency of the fabrics used in this study is not a function of temperature in the range of the current study ($20^{\circ}C \le T \le 120^{\circ}C$). It is also found that, in the visible spectrum, the transparency of the fabrics does not vary with humidity as long as water in the liquid phase is not present in the fabric. Water droplets adhering to the fabric affect the local optical transmittance significantly by reflecting and refracting the light beams, which reduces the accuracy of the measurement until the droplets evaporate. Another limitation of the transparency measurement technique is that the transparency of paper changes under high mechanical pressure. However, such effects are negligible for mechanical pressures less than 30 kPa (section 2.3), which is far above the maximum stagnation pressure of this study.



Figure 5.1 Schematic of optical measurement to infer paper moisture content. $I(\lambda)$ is the light intensity. *T*, *RH*, and *P* show air temperature, relative humidity and pressure, respectively. (The paper thickness is exaggerated.)

5.2.2 Experimental Apparatus

An experimental apparatus was designed and built to simulate the through air drying process under various drying conditions (Figure 5.2). An air pressure regulator, connected to a compressed air line, filters and reduces the pressure to 400 kPa to feed the mass flow controller unit (MFC) safely. The Aalborg® GFC57 MFC unit provides an adjustable flowrate of $\dot{m} \leq 3.2 kg/m^2 s$ through the paper sample of 35 mm by 35 mm using a built-in closed loop control system. The air supply has a temperature and absolute humidity of $T = 20 \pm 0.6$ °C and $\omega = 1.43 \pm 0.51 g/kg$ ($RH \approx 10\%$), respectively. A pair of pressure transducers are utilized to measure the static pressure of the air at the MFC outlet and directly ahead of the paper sample. Data from the feedback generated by the MFC, thermocouples and pressure transducers are collected using a National Instruments® data acquisition system (DAQ). A LabVIEWTM program drives the DAQ system, which is capable of running the experiments under constant mass flowrate and constant pressure schemes. In this research, all experiments were conducted under constant mass flowrate condition.

The airflow passes through three insulated inline heaters with a cumulative power of 5.2 kW. The heater units can operate and be controlled independently to reach the desired power necessary for a specific flowrate and temperature. A proportional-integral-derivative (PID) controller maintains the temperature of air at the set point and monitors the maximum temperature to remain lower than the safety limits of the apparatus. To preheat the system and reach steady state conditions before each experiment, a three-way valve directs flow to a vent while the heaters are active. Air leaves the system through a control valve that is adjusted to set the pressure loss of the purging system to be equal to the main flow path. A FLIR® U3-32S4M-C CMOS camera is employed to capture the transmitted light during the experiments. The camera uses a Fujinon® HF25SA-1 lens which is mounted on the main channel as shown in Figure 5.2. Clear optical access to the paper is provided by a quartz glass window. The paper sample is placed on the TAD fabric which is mounted firmly on the second part of the channel. An adjustable LED light source provides even and steady illumination on the fabric side. Northern bleached softwood kraft (NBSK) handsheets with a constant basis weight $(35.0 \pm 1.4 g/m^2)$ and negligible permeability differences were used in the experiments. The paper samples were prepared based on the standard TAPPI procedure (T205 sp-02) at the Pulp and Paper Center, University of British Columbia, Vancouver, BC, Canada. NBSK is chosen since it is known as the standard benchmark paper in the pulp and paper industry.



Figure 5.2 a) Schematic and b) photo of the experimental apparatus. The drawing is not to scale.

Four commercially available TAD fabrics, manufactured by AstenJohnson Inc., are used in the experiments. The properties of the fabrics, including their air permeabilities are detailed in Table 5.1. The permeability values, reported by the manufacturer, represent the superficial flowrates of

air at standard temperature through the unit surface area $(1 ft^2)$ when a pressure difference of 125 *Pa* is applied. The contact spots are the regions of the paper surface where the paper and fabric are believed to be in physical contact. The portion of the surface area of the paper occupied by the contact spots is defined as contact area. The contact area and geometrical properties of the fabrics are measured using a Thorlabs® TELESTOTM-II Spectral Domain OCT device. The raw data generated by the OCT is fed to an image processing code to measure the surface area of the fabrics using a technique described in section 4.2.3. The fabrics are constructed using a similar polymer material with identical surface properties (e.g. water-air interface contact angle) and no microscale surface features.


Figure 5.3 a) Reflected-light-microscopic images of the TAD fabrics, b) orthogonal views captured by OCT, and c) maps of contact points. Photos show the paper side and the vertical axis corresponds to the machine direction (MD). The field of view for F1 and F2 is 4.5 mm by 3.5 mm and for F3 and F4 is 9.0 mm by 7.0 mm.

Table 5.1 Commercial name, air permeability at 125 *Pa* and structural properties of the TAD fabrics, as provided by the manufacturer. The contact area and average area of contact spots are determined from OCT measurements.

| ID | Commercial Name | Permeability (cfm/ft ²) | Fabric Weight (Ibs/1000 ft ²) | Contact Area (%) | Average area of contact spots (µm ²) | Weave Pattern |
|----|----------------------------|--|--|---------------------|--|-------------------------------------|
| F1 | MonoFlex® | 590 | 51.9 | 16.8 | 53221 | 1,4 BT; Long Wrap Down |
| F2 | InTegra® ExFT | 415 | 58.5 | 33.5 | 53758 | Top: 2,1 Twill Bottom: 4 Shed BT |
| F3 | MonoShape [™] MF | 865 | 80.1 | 10.1 | 99440 | 1,4 BT; Long Wrap Down |
| F4 | MonoShape [™] M44 | 500 | 127.6 | 6.6 | 116880 | 1,4 BT; Long Wrap Up |

5.2.3 Experimental Procedure

Before each experiment, the three-way valve exhausts the flow through the control valve until steady state conditions are reached. The control valve sets the total pressure loss of the purging path to be equal to the pressure loss of the main flow path with the presence of the wetted paper sample. This prevents flow fluctuations after switching the flow into the main experimental channel. An accurate amount of water is added to the paper using a micropipette until the overall moisture content reaches the desired value. To reach an even moisture distribution, the wet paper is kept in a sealed chamber for five minutes after which the wet paper sample is placed on the TAD fabric. Then, the second part of the channel (Figure 5.2) is securely latched to the main channel. Drying begins once the three-way valve is actuated, re-directing the air flow through the fabric and paper from before the three-way valve actuation to after drying is complete. Depending on the experimental conditions, the frame rate of the camera may be as high as 100 Hz and the light intensity and exposure time must be adjusted accordingly. The experiment continues until the paper is completely dried. An image processing code is developed to post process the recorded

images and calculate the moisture content distribution using a unique calibration for every measuring window, as described in chapter 2.

The drying experiments are carried out under different drying conditions and for all dryer fabrics. The effect of air temperature is studied in a range of 20° C $\leq T \leq 120^{\circ}$ C at the flowrate of $\dot{m} = 1.6 kg/m^2s$, and the effect of flowrate is investigated over the range $0.80 kg/m^2s \leq \dot{m} \leq 3.20 kg/m^2s$ while the temperature is set at $T = 20^{\circ}$ C. This way a broad range of drying intensities can be achieved as described in section 5.3.1. Because the measurement technique is able to resolve the moisture content distribution, the drying non-uniformity and the correlation of the drying pattern with the grammage distribution of paper can be investigated over time. The grammage distribution of the samples was measured using an Ambertec® Beta Formation Analyzer with a spatial resolution of 1 mm at FPInnovations, Pointe-Claire, QC, Canada.

5.3 Results and Discussion

5.3.1 Effect of Drying Parameters

Figure 5.4 shows the spatially average drying information for a wet paper mat on fabric F3. The effect of different air mass flowrates and temperatures on average paper moisture content is illustrated in Figure 5.4a and Figure 5.4c, respectively. The corresponding drying rate versus moisture content is sketched in Figure 5.4b and Figure 5.4d. As can be seen in Figure 5.4b and Figure 5.4d, the drying process lacks a constant rate stage except at extremely low intensity drying $(\dot{m} = 0.80 \ kg/m^2 s)$. This finding is consistent with that of other researchers [30, 31, 38]. In low intensity drying (low air temperature and flowrate), the drying rate has a sharp maximum at the beginning (MC = 200%), as can be seen in Figure 5.4b for $\dot{m} \le 1.60 \ kg/m^2 s$ and Figure 5.4d for $T = 20^{\circ}$ C. The sudden decrease in drying rate after the maximum is caused by the sudden temperature drop resulting from the evaporation latent heat. As air passes through the paper, the

latent heat of evaporation can drop the temperature down to the wet bulb temperature, resulting in a drop in the drying rate [30]. The average values of critical moisture content (defined in section 4.3.2 as CMC) measured here are in excellent agreement with the results under the same drying conditions presented in reference [30]. The measured values of CMC are corresponding to the maximum drying rates shown in Figure 5.4b and Figure 5.4d. The pressure drop through the paper and fabric is sketched in Figure 5.4a for one case. The pressure drop decreases by about a factor of 4 during drying, primarily as a result of evaporation of water droplet from the paper pores, which increases the paper void fraction.

The air permeability of paper has also been shown to irreversibly increase after a complete cycle of wetting and drying. For example, if dry paper is placed in the device and the temperature and mass flowrate are set at T = 20°C and $\dot{m} = 1.60 kg/m^2 s$, the pressure drop through the paper is measured to be 6.01 *kPa*. If the same paper sample is wetted and dried in the apparatus under the same conditions of temperature and mass flow rate, the pressure drop through the paper is measured to be 3.54 *kPa*, a 41% decrease relative to that of the paper sample prior to wetting and drying. This sharp rise in paper permeability is indicative of significant structural changes in the paper. The relation of permeability with moisture content and the structural effects of wetting and drying on paper is discussed in detail in reference [30]. Since the changes in the structure of the paper may affect its optical properties, the validity of calibration functions have been verified gravimetrically. The gravimetric results proved the validity of the measurement with an uncertainty of less than 3.8%.



Figure 5.4 Trend of drying under different conditions and for fabrics F3. Effect of flowrate on a) moisture content as a function of time and b) drying rate are shown at $T = 20^{\circ}$ C. The effect of air temperature at $\dot{m} = 1.6 kg/m^2 s$ is shown in (c) and (d). An example of pressure as a function of time, corresponding to $\dot{m} = 1.6 kg/m^2 s$ is shown in (a).

5.3.2 Effects of Dryer Fabrics

To study the effect of fabric properties, experiments were repeated under different conditions for four different fabric types (Table 5.1). Drying time variations, as a function of flowrate and temperature are illustrated in Figure 5.5a and Figure 5.5b, respectively. As expected, the drying time decreases significantly with both flowrate and temperature for all fabrics. However, the effect

of temperature on drying time is much greater than the influence of flowrate. Although the relative difference of drying times is small for different fabrics at low drying intensities, for high intensity drying, the drying time may change significantly from fabric to fabric. Under industrially realistic conditions, the intensity of drying is very high as the typical air temperature and driving pressure are $T \approx 200^{\circ}$ C and $\Delta P \approx 7 kPa$ [31, 37, 45], respectively. This means that the impact of the dryer fabric on the drying efficiency can be significant. For instance, at temperature $T = 120^{\circ}$ C and flowrate $\dot{m} = 3.20 kg/m^2 s$, the drying time of fabric F1 is 43% shorter than fabric F4 (Figure 5.5b).

The drying time difference of the fabrics showed no relationship with the permeability presented in Table 5.1. Comparing Figure 5.5b with information in Table 5.1, it can be observed that drying time decreases with or is independent of contact area. Obviously, the inverse correlation or the independence of contact area and drying time can only happen while the total contact area is small enough; a 100% contact area would imply zero permeability and a very slow drying rate. Intuitively one would expect that a low contact area would be associated with a fast drying time. Since air passes easily through noncontact regions, they become dry by the through air drying mechanisms of heat and mass transfer. The contact parts, on the other hand, lose their moisture through surface evaporation and lateral diffusion, which is generally a slower mechanism [1, 28, 87]. In low intensity drying, the characteristic time of drying is long, so there is enough time for water to diffuse laterally in the paper sheet, rendering the effect of spatial non-uniformities of the dryer fabric to be negligible. When the intensity of the drying increases, a relationship between drying time and structural properties of the fabrics starts to appear since the drying time becomes comparable and shorter than the characteristic diffusion time [87].



Figure 5.5 Variation of drying time vs. a) mass flow rate at T = 20 °C and b) air temperature at a flow rate $\dot{m} = 1.60 \ kg/m^2 s$.

To further investigate the effect of contact area, the average contact area of fabric F4 was increased artificially, by blocking a small rectangular spot at its center, to reach the average contact area of fabric F1. Experiments on this modified fabric showed that the drying time is four times

the drying time of fabric F1, which is above the drying time of all other fabrics as well. This finding suggests that the distribution and shape of the contact spots is probably a key parameter. The average area of contact regions results in the best correlation with the drying time in high intensity drying. The average area is a suitable indicator of the distribution of contact area since all contact regions have similar geometry with circularity of $c = 0.40 \pm 0.05$. A weaker but monotonic correlation with the average perimeter, Feret diameter and minimum Feret length of the contact regions is also observed. Feret diameter and lengths are defined in reference [113]. All these correlations become negligible for low intensity drying, $T < 60^{\circ}$ C and $\dot{m} \le 1.60 kg/m^2 s$.

For all fabric-paper mats, the pressure drop is a function of the mass flow rate and follows the Darcy–Forchheimer law [30], as shown in Figure 5.6a. The viscosity of air increases with temperature almost linearly in the range of this study ($20^{\circ}C \le T \le 120^{\circ}C$), resulting in the gradual increase in the pressure drop at constant mass flowrate seen in Figure 5.6b. As seen in Figure 5.6, fabrics with a finer structure have a higher pressure drop through the combined fabric-paper mat. The vast majority of the pressure drop through the fabric-paper mat is due to the paper, as the flow resistance of the fabrics is small. For example, the pressure drop of fabric F2 at $T = 20^{\circ}C$ and $\dot{m} = 1.60 \text{ kg/m}^2 \text{s}$ is below 90 *Pa*. Therefore something about how the drying paper interacts with the fabric causes fabrics with a coarser weave structure to produce dried paper with higher permeability. We hypothesize that for fabrics with a coarse weave, the pressure drop across the wet paper mat causes it to be embossed into the fabric shown in Figure 5.7. This embossing both increases the mat area and would likely open up the paper structure at the level of the fibers, both of which should increase permeability [30]. The mechanism of the paper deformation and surface properties is discussed in reference [30].

Under realistic conditions, increasing the pressure drop may increase the cost of drying. Under constant driving pressure, which is the typical condition on a papermachine, coarser fabrics result in higher mass flowrate, which will in turn increase drying efficiency. Papermakers contemplating the use of a coarser TAD fabric would need to compare the benefits associated with a higher efficiency with the possible detrimental effects of an embossed paper sheet.



Figure 5.6 Variation of dry pressure drop vs. a) mass flow rate at $T = 20^{\circ}$ C and b) air temperature for $\dot{m} = 1.60 \ kg/m^2 s$.



a) Before wetting and drying b) Fabric F2 c) Fabric F3

Figure 5.7 Embossed pattern on the paper caused by the structure of the fabrics after one cycle of drying. The field of view is 9 *mm* by 7 *mm* and the vertical axis corresponds to the machine direction (MD).

5.3.3 Spatial Drying Pattern

Using the current experimental apparatus, maps of moisture content over time can be visualized as shown in Figure 5.8. Multiple experimental repeats under identical experimental conditions and for all fabrics reveal that the pattern of drying is superficially random. Drying always starts at one or a few nucleation sites, and the dry patches then grow in size until eventually the whole sample becomes dry. On the other hand, a relatively strong correlation in the spatial pattern of drying is observed when the same paper sample is used for two or more cycles of drying which is not a typical practice in production process. The correlation coefficient of the moisture content distribution between the first and second cycle of through air drying is $R = 0.75 \pm 0.15$, which is high. However, it should be borne in mind that a cycle of wetting and drying alters the paper structure irreversibly [30], and thus the high correlation between the first and second cycle of through and drying alters the paper structure irreversibly alteration to the structure of the paper that causes the drying pattern to happen similarly in subsequent cycles.

To investigate the correlation of the paper grammage and moisture content distribution over time, R is calculated during the drying of samples with a known grammage distribution

(formation). The grammage maps were measured with the spatial resolution of 1 mm using an Ambertec® Beta Formation Analyzer prior to the experiments. The results showed a relatively constant, but weak, correlation, of $\overline{R} \approx 0.23$ between the moisture content distribution and the map of grammage for all samples while the average moisture content varies in the range $30\% \leq \overline{MC} \leq 150\%$. We speculate that the correlation is not higher because of the large impact of the drying nucleation, which occurs at much larger scales than variations in paper grammage. A monotonic relationship between the grammage and permeability and drying time is also reported in reference [48], but in that reference the relationships are established at the scale of an entire sheet, rather than locally within a single sheet. The correlation of local permeability of paper with the spatial pattern of drying can be a subject of future studies.

| (a-c) | MC (%) | 0 | 50 | 100 | 150 | 200 |
|---------|------------|----|------|-----|------|-----|
| (d-e) | MC (%) | 0 | 25 | 50 | 75 | 100 |
| (f) For | mation (g) | 30 | 32.5 | 35 | 37.5 | 40 |
| | | | | | | |





a) t = 0s

b) t = 3s

c) *t* = 6*s*



d) t = 9s e) t = 12s f) Formation

Figure 5.8 a-e) Contours of moisture content in paper at different times (t) during the drying. Air temperature and flowrate are set at T = 20°C and $\dot{m} = 1.6 \text{ kg/m}^2\text{s}$, respectively. f) Map of grammage distribution (formation) of the paper sample measured using Beta Formation Analyzer. Fabric F3 is used and the field of view is 30 mm by 30 mm.

5.4 Conclusions

In this chapter, the optical transparency measurement technique has been used to investigate the effect of dryer fabric characteristics on the through-air-drying process. Four commercially

available fabrics with different permeabilities and geometric properties are studied under various drying conditions. No statistically significant correlation between the drying time and permeability is observed in the range of this study. Although all fabrics had a similar drying time when the drying intensity is sufficiently low, for high intensity drying the geometric properties of the fabric affect the drying process. During high intensity drying, fabrics with large areas of contact with the paper are associated with slower drying. The reason for this is that the fabric filaments are impermeable, and thus water must travel laterally over a longer distance than would be the case for a fabric with small contact areas. In contrast, under low intensity drying conditions the comparatively low lateral diffusivity of water plays a smaller role, and all dryer fabrics have similar drying times. Fabrics with a coarser weave structure produce dried paper with higher permeability. For fabrics with a coarse weave the unsupported length of wood fibers is greater, and thus the pressure drop across the wet paper mat causes it to be embossed into the fabric more significantly. This embossing increases the mat area and alters the paper structure at the level of the fibers. Spatial maps of moisture content were compared with the local grammage distribution of the paper, showing that there exists a correlation between the spatial pattern of drying and the grammage distribution of the paper. As one would expect, regions of the paper with locally higher grammage are associated with slower drying rates.

Chapter 6: Summary and Recommendations

6.1 Achievements

The key findings of this research have been explained in the conclusions sections of chapters 2, 3, 4, and 5. Major advancements and contributions of this research can be briefly summarized as follows:

- A new optical method for moisture content measurement in paper has been developed and characterized. As described in chapter 2, the technique has provided substantial advantages and made accurate measurement of moisture content distribution possible.
- Development of the one-sided transparency measurement technique offered a unique way to quantify the optical transparency when access to one side of the object is restricted. This makes it possible to measure the distribution of moisture content of paper when it is sandwiched between the heater surface and the dryer fabric (chapter 3).
- Using the developed measurement methods, the effect of dryer fabric characteristics on the drying process under realistic conditions of a multi-cylinder dryer is investigated. For the first time, the effect of structural properties of dryer fabric on drying is quantified. This quantification led to establishing recommendations for selection of contact dryer fabrics for different applications, as described in chapter 4.
- The effect of the dryer fabric on through air drying has been studied taking advantage of the developed measurement method. As shown in chapter 5, it has been observed that the geometry of fabric contact points can affect the drying efficiency under high drying intensity conditions.

In the following sections, the limitations of the current research will be summarized and recommendations for future research will be proposed.

6.2 Limitations

The limitations of the measurement techniques and the experimental studies are explained in their corresponding chapters. In this section, the most important limitations are summarized.

As discussed in chapter 2, measurement of moisture content using optical transparency has a number of limitations. The spatial resolution of the method is limited to the sample properties such as the thickness, porosity, and scale of structural non-homogeneities. The dry material (paper web) must be translucent (if not transparent) at the wavelength of the measurement. Depending on the type of paper, the transmittance of paper can be a function of mechanical pressure. If an immense mechanical pressure is applied on the paper, it may result in bias error in the measurement. The effect of pressure must be calibrated and isolated, which adds to the complications of the measurement. In all cases, the upper range of the measureable moisture content is limited due to saturation of the sample or a sensitivity drop that may happen before paper sample gets saturated.

Using the one-sided measurement technique may also result in some limitations. The optically blocked side of the sample, in this thesis the fabric, must be auto-fluorescent or has to be coated with a fluorescent dye. The sample itself should have no auto/fluorescent yield at the emission wavelength as otherwise the fluorescent response may not be distinguished from the transmitted light. The one-sided measurement technique reduces the spatial resolution of the measurement, particularly if the sample is thick. The result of the measurement will be the geometric mean of the optical transmittance at excitation and emission wavelengths. Therefore, transparency measurement at a single wavelength band is not possible.

As described in chapter 4, the experimental apparatus for multi-cylinder dryer investigations has some limitations both in the measurement capabilities and the operational range of drying parameters (Table 4.2). The results of this study only show the effect of dryer fabric on the efficiency of the second phase of multi-cylinder drying (section 1.1.1), however, other effects of the fabric such as its impact on the product's surface properties and runnability have not been considered. Additionally, only a limited number of contact dryer fabric types have been studied, and this is also true of the TAD fabrics. In the current research, the intensity of TAD (maximum flowrate and temperature) is limited due to the safety concerns. In some paper machines, the intensity of drying can be above the limits of this study.

6.3 **Recommendations for Future Work**

Since the current research presents a novel moisture content measurement method, there exist a number of potential research directions based on this method that could be conducted in the future:

- The measurement technique can be used to study the effect of press felt on the mechanical dewatering of paper in the press section. Due to the high mechanical pressure in that section, the technique must be calibrated with respect to pressure, requiring a comprehensive study.
- The developed technique can be used to measure the water (or other liquid) content in other porous media. For example, current methods to study water and/or oil transport in sand can be improved with the presented technique.
- Using the developed technique, the water transport in paper (e.g., during paper wetting) can be studied accurately. Analytical and numerical models can be developed and/or improved based on the experimental results.
- The effect of alternative fabric designs on the drying has not been studied. Particularly, new nonwoven fabric designs can be easily examined with the current method.
- More TAD fabric types under a broader range of conditions must be studied to gain a better statistical confidence in the results.

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