Measurement of the Dielectric Properties of Paper

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Abstract

Dielectric properties of non-impact printing papers are seldom measured. However, dc resistivity alone does not predict the behavior of paper very well when paper passes through a transfer nip. If the electric field changes with time, all anisotropic frequency-dependent electrical properties of paper should be considered.

We present a new method for the measurement of the electrical properties of paper in the principal directions of the sheet. In the frequency range from 20 Hz−1 MHz, permittivity ε' and dielectric loss factor ε'' or electrical conductivity σ can be measured. Results on coated and uncoated commercial papers are presented.

Introduction

In the transfer step of electrophotographic printing, paper is polarized by a strong electric field and the oppositely charged toner is attracted to the paper surface.[1] The electric field is usually applied using a high voltage corona or a bias roll. With increasing printer speed, the dwell time of paper in the transfer zone decreases and dynamic properties of paper become important.

Of the electrical properties that characterize paper, (dc) surface resistivity is the one most extensively used.[2] Unfortunately, dc resistivity is not well defined and it poorly represents the electrical behavior of paper. Even though several authors mention the significance of permittivity (dielectric constant) to the toner transfer efficiency, dielectric properties of paper have not been studied.[3−7] To fully account for the toner transfer efficiency, one should consider both the permittivity and the resistivity of the paper. As an example, transfer efficiency has been found to correlate better with charge decay rate (that includes the effect of permittivity) than with resistivity alone.[3] However, the paper industry has not yet adopted any measurement method to serve this purpose.

In this paper, we present a method for the measurement of the dielectric properties of paper. The effect of moisture content on the dielectric properties of commercial papers are presented.

Dielectric Properties of Paper

Permittivity ε describes the polarisability of the material in an external electric field. Since the values of permittivity are of the order of 10^{-11} As/Vm, it is more convenient to use the dielectric constant κ which is the ratio of the permittivity of the material and the permittivity of vacuum $\kappa=\varepsilon/\varepsilon_0$. Values of the dielectric constant range from 2 for most polymers up to 10^3–10^4 for ferroelectric materials such as Barium Titanate.[8] The dielectric constant of dry paper is typically 2−4, but it can be higher depending on density, filler content, fiber furnish, etc.

When an external electric field is applied to a dielectric, the charges in the dielectric are displaced so as to reduce the electric field inside the material. Positive charges of non-polar molecules move in the direction of the applied field and negative charges in the opposite direction. The displacement of charges depends on the forces opposing the movement and on the strength of the applied electric field. If polar molecules are present, their electric dipoles tend to align with the direction of the field. This further increases the polarization of the material. The larger the permittivity of the material, the stronger is the polarization.[9]

Permittivity is frequency dependent. As frequency increases, slow polarization mechanisms cannot keep up with the rapidly changing electric field and the polarization mechanism relaxes, i.e. it no longer contributes to the polarization. This reduces the dielectric constant. If there is a well-defined relaxation frequency for the polarization mechanism, it causes a distinct drop in the dielectric constant spectrum and a corresponding peak in the dielectric loss spectrum.[10] Due to the large number of different polarization mechanisms that exist in paper, no well-defined relaxation frequencies are seen at sub-optical frequencies.

Dielectric properties are affected by the moisture in paper. The dielectric constant of water is 78.4; over one order of magnitude larger than that of paper.[8] This is not surprising considering that water molecules have a permanent dipole moment. However, water molecules in paper are neither free to move around nor free to choose their orientation. This means that their effective dielectric constant is much smaller than that of free water and depends on the orientation of the electric field.[11]

A water molecule attached to a cellulose chain is relatively free to orient itself parallel to the field only if the field is parallel to the cellulose chain. If the field is perpendicular to the chain, the orientation is inhibited by the presence of the chain. Since cellulose chains in paper point in different directions, only a small fraction of the water molecules can align perfectly with the electric field. Hence, water in paper has a relatively small effect on the dielectric constant at low moisture contents.

The dielectric constant of paper is greater along the sheet plane than in the z-direction. In addition, in sheets with fiber orientation the dielectric constant has a maximum at the direction of the fiber orientation angle. This fact can be used in the measurement of fiber orientation angle and strength.[12]

An increase in the dielectric constant is found with increasing density. The density dependence of the dielectric constant is given with reasonable accuracy by the Clausius-Mossotti relation[13]

$$\frac{\kappa' - 1}{\kappa'' + 2} \propto \rho_d \qquad (1)$$

where κ' is the real part of the complex dielectric constant and ρ_d is the density of paper.

The contribution of fillers to dielectric properties is interesting. E.g. the dielectric constant of a typical filler material, CaCO3, is 8.3–8.7 at 94 GHz depending on the orientation of the field.[8] Fillers therefore increase the dielectric constant of paper.

Measurement of Dielectric Properties

The sensor head is shown in Fig. 1. The paper is placed between two printed circuit boards. Interdigited electrodes on the boards can be connected with relays in two ways: 1) The electrodes of one board are connected in parallel and the impedance between the electrodes of the boards is measured. In this configuration the electric field points through the paper and thus parameters in z-direction are measured. 2) The electrode of one board is connected to the facing electrode of the other board. In the impedance measurement, the electrodes from two sets are connected to opposite potentials. This connection measures the in-plane electric properties of the paper (Fig. 1). The length of the electrodes and their lateral extent are such that the sensor measures the electric properties averaged over an area of 41 by 36 mm^2.

The impedance between the electrode sets is measured with a Hewlett-Packard Precision LCR Meter, 4284A. The measurement is controlled with a PC microcomputer. The PC sets the relays in z-direction (ZD) and machine direction (MD) configuration and the impedance at predetermined frequencies is measured.

The sensor head is calibrated with a PTFE sheet. In the frequency range used in this study, it is a perfect insulator with a relative permittivity of 2.10 at room temperature. For taking into account the effect of the wide conductivity, permittivity, and thickness ranges of paper samples on the electric field distribution in the sensor head, a two-dimensional FEM (Finite Element Method) simulation program (Maxwell 2D Parameter Extractor, Ansof Corp.) was employed. Calibration parameters computed with the program were stored in a look-up table for different frequency, permittivity, conductivity, and thickness of the sample. An interpolation algorithm uses these values when computing the sample conductivity and permittivity from the measured impedance and sample thickness values.

The available measurement frequency range is limited by the LCR meter to 20 Hz–1 MHz. At low frequency and high relative humidity the reliability of the measurement suffers from conduction losses. Below 50% RH the standard error is typically 5% or less.

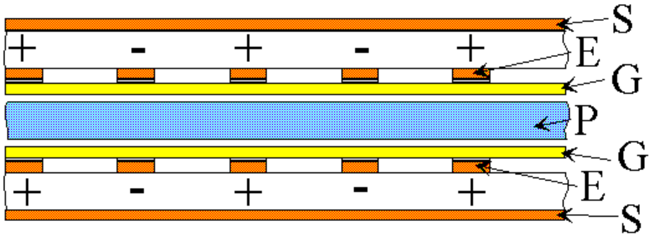

Figure 1. Partial cross-sectional view of the sensor head of the dielectric analyzer DIANA. The copper Electrodes (E) are machined on printed circuit boards whose other side's copper layers (S) act as guards. The paper (P) is inserted between two glass plates (G). The width of the electrodes is 200 μm and their center-to-center distance is 600 μm.

Results and Discussion

We studied three coated papers with basis weight of 130 g/m^2, one coated paper of 80 g/m^2, and five copy papers with different basis weights ranging from 80 to 100 g/m^2. In addition, one copier transparency made of poly(ethylene terephthalate) (PET) was measured. All samples are commercially available printing media.

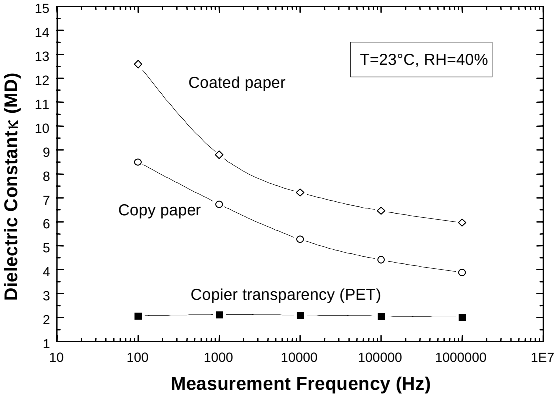

Figure 2. Dielectric constant κ_x' vs. measurement frequency for various printing media at 40% RH.

The dielectric constant and dielectric loss factor of each sample was measured as a function of frequency in the machine direction and z-direction. Ac conductivity was calculated from the dielectric loss term[9]

$$\sigma = \omega\varepsilon'' = 2\pi f \kappa'' \qquad (2)$$

where f is frequency and κ'' the measured dielectric loss term. Hence, electrical conductivity is a deduced quantity.

Figure 2. shows the machine direction dielectric constant of three samples against frequency at 40% RH. It clearly shows that the dielectric constant relaxes at high frequencies but there is no well-defined relaxation frequency. No dielectric relation is observed in the PET film

even though literature suggests that there should be a slight decrease as a function of frequency. The measured value 2.1 differs from the value 3.25 found in the literature, measured for a Mylar film.[8]

Figure 3 shows the effect of moisture content on the dielectric constant of paper. The range of moisture contents corresponds to relative humidities of 20%–50% RH.

In spite of its lower moisture content, the coated paper has a higher dielectric constant than the copy paper. This can be attributed to the higher mineral content (40.2% vs. 21.3%) and higher density (1320 kg/m^3 vs. 750 kg/m^3) of the coated grade. Basis weight and thickness do not affect the results. This was verified by measuring papers in a basis weight range of 70–250 g/m^2 having the same mineral content and density. No basis weight dependencies were found.

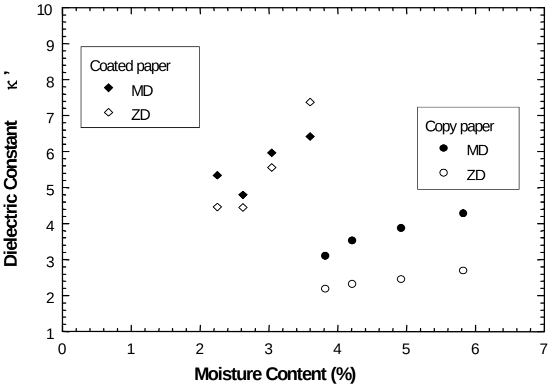

Figure 3. Dielectric constant κ' of coated paper and copy paper as a function of moisture content in machine direction (MD) and z-direction (ZD). (f = 1 MHz.)

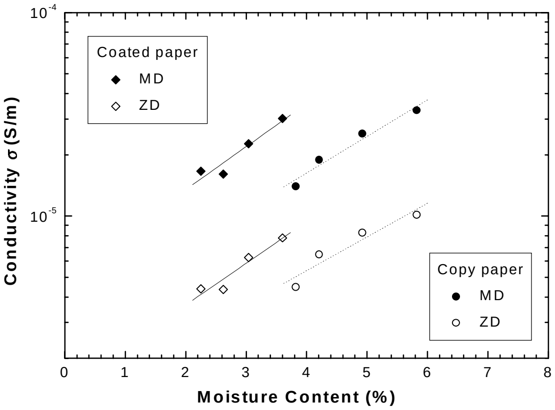

Figure 4. Electrical conductivity σ of coated paper and copy paper as a function of moisture content in machine direction (MD) and z-direction (ZD). (f = 1 MHz.)

As expected, the dielectric constant increases as a function of moisture content because the dielectric constant of water is higher than that of paper. The behavior of the paper samples resembles previously reported data.[14] In the coated paper the dielectric constant increases at a faster rate in the z-direction than in the machine direction. This could be due to the layered structure of the coated grade.

The effect of moisture content on the ac conductivity at 1 MHz (Fig. 4) is not as great as on dc conductivity.[15] On the other hand, differences between samples are smaller in the ac measurement. As expected, conductivity is larger in the plane of the sheet, probably due to the fact that charge carrier mobility is higher parallel to the fibers.[16]

The relationship between the charging capacity (maximum voltage) and dielectric loss term in the z-direction at 40% RH is plotted in Fig. 5. Charging capacity is the electrostatic potential measured above the surface of the specimen after charging it with a HV corona for a predetermined time.[17] After charging, the corona wires are rapidly moved aside and the measurement starts.

The drop in the measured potential as a function of dielectric loss factor can be explained as follows. If the dielectric loss factor is high, then the charge decay time is small and the voltage drops quickly. In all the samples but PET charge decay starts already before the actual measurement starts, resulting in a lowered maximum voltage.

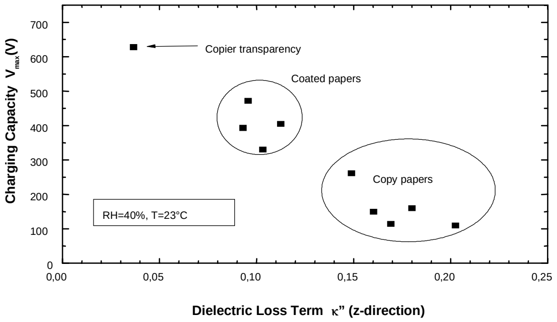

Figure 5. Charging capacity (maximum voltage) as a function of dielectric loss factor κ_z'' (f = 1 MHz). Different types on printing media are grouped for clarity.

Summary

The method presented in this paper has proven to be useful. The measurement is both easy and relatively quick to perform. The results presented demonstrate that paper is an anisotropic dielectric material. This anisotropy is related to the structure of the paper, i.e. fiber orientation, coating layers, etc.

Since moisture has a significant effect on the dielectric properties, it is important to control the moisture content of the samples. This includes proper conditioning prior to the measurements. Due to dielectric relaxation, the frequency should always be quoted when results are presented.

Acknowledgements

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Biography

Sami Simula received his M.Sc. degree in Solid-State Physics from the Helsinki University of Technology in 1995. Mr. Simula is currently a postgraduate student working at the Finnish Pulp and Paper Research Institute (KCL). His current research project involves the electrical and thermal properties of paper.

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